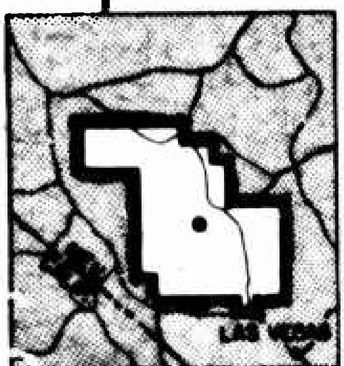
WT-1429

OPERATION
PLUMBBOB



NEVADA TEST SITE
MAY-OCTOBER 1957

Project 4.2

EVALUATION of EYE PROTECTION AFFORDED by an ELECTROMECHANICAL SHUTTER

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OPERATION PLUMBBOB—PROJECT 4.2

EVALUATION of EYE PROTECTION AFFORDED by an ELECTROMECHANICAL SHUTTER

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ABSTRACT

This project's objective was to evaluate a high-speed electromechanical shutter that had been developed as a protective device against flashblindness.

The shutter was tested during five shots by the use of animal and human subjects. The thermal energy incident on the shutters ranged from 0.0347 to 0.1804 cal/cm^2. Illumination incident on the shutters ranged from 13,200 to 120,000 lumens/ft^2. The shutter closure time was 550 ± 50 μsec. Recovery after exposure of visual effectiveness of personnel protected by the shutter was instantaneous and complete, whereas unprotected animals received chorioretinal burns. It was concluded that a shutter of the type tested during this operation offered protection from flashblindness. The electromechanical shutter was sufficiently developed to be incorporated into a goggle for service testing.

A simple relationship is also given for scaling peak photometric illumination against peak thermal irradiance.

FOREWORD

This report presents the final results of one of the 46 projects comprising the military-effects program of Operation Plumbbob, which included 24 test detonations at the Nevada Test Site in 1957.

For overall Plumbbob military-effects information, the reader is referred to the "Summary Report of the Director, DOD Test Group (Programs 1-9)," ITR-1445, which includes: (1) a description of each detonation, including yield, zero-point location and environment, type of device, ambient atmospheric conditions, etc.; (2) a discussion of project results; (3) a summary of the objectives and results of each project; and (4) a listing of project reports for the military-effects program.

PREFACE

The project officer desires to express appreciation to the following commands and individuals for their outstanding cooperation in furnishing the personnel who made completion of this study possible. Lt. Colonel Paul H. Andrae II and the Tactical Air Command for the personnel who acted as subjects and did a remarkable job under adverse conditions; the School of Aviation Medicine, USAF, and especially to Colonel Richard S. Fixott, for furnishing the examiners and animals for this participation; Nellis Air Force Base and especially the personnel of the base hospital for the wholehearted assistance and cooperation given to project personnel during the test period; Richard P. Day and the personnel of the U. S. Navy Radiological Defense Laboratory for thermal measurements assistance, and counsel given at all hours of the day and night; and the personnel of the Aero Medical Laboratory, Wright Patterson Air Force Base, Ohio, who did so much to make the project possible but are too numerous to mention indivually.

CONTENTS

TABLES

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Chapter 1
INTRODUCTION

This project was designed to test the effectiveness of a prototype electromechanical shutter against flashblindness incurred during tactical air operations. Flashblindness is a temporary decrease in visual acuity characterized by a relative scotoma and adaptation of the eye to a high level of illumination.

1.1 OBJECTIVE

The objective of this test was to determine the effectiveness of an electromechanical shutter in preventing or minimizing flashblindness.

1.2 BACKGROUND

Initial work of this type was performed by Colonel V. A. Byrnes and others of the School of Aviation Medicine, USAF, during Operations Snapper, Buster-Jangle, and Upshot-Knothole. Results of thier work were utilized, where applicable, to determine the type of protection that has been and is being developed.

Results of previous field studies (References 1, 2 and 3) give some indication of recovery times when the detonation is viewed directly. The studies indicate that 75 seconds are required to read red, internally lighted instruments after the detonation is directly viewed through a red goggle transmitting approximately 22 percent of the total thermal energy. The time was reduced to 8 seconds when auxiliary floodlighting of the instruments was employed. Visual acuity of 0.1 returned in an average of 17 seconds and acuity of 0.5 in 195 seconds, as measured with a nyctometer with a background brightness of 0.37 feet-lamberts (ft-L).

An ophthalmic filter that transmitted approximately 5 percent of the total thermal energy and was limited to the spectra between 0.60 and 0.68 micron permitted viewing red floodlighted and internally red lighted instruments in an average of 18.4 seconds. Visual acuity of 0.1 returned in an average of 35.5 seconds and 0.5 acuity in 153 seconds.

These results are the most severe to be expected. If the subject is not looking directly at the detonation, recovery time will be drastically reduced. Light falling on the fovea, the retinal area of most acute vision, will consist mainly of scattered light or reflected light and will be considerably less than when the fireball is viewed directly.

Furthermore, the random chance that an individual will be directly viewing the detonation is remote (Reference 1). Many of the calculations offered as indicating the remoteness of this possibility are somewhat misleading, as the visual acuity would probably be severely affected if the retinal image was within 5 degrees of the macular area.

Past field tests indicate that the problem of flashblindness is largely confined to the nighttime situation. Ordinary ophthalmic filters may reduce the effects of glare but cannot be depended on to absolutely prevent chorioretinal burns. Chorioretinal burns have been obtained on animals at and beyond 40 miles with a large pupillary aperture and under ideal atmospheric conditions (Reference 1). Atmospheric transmission is of extreme importance in the determination of a safe viewing condition. Rate of delivery

of the thermal energy is also extremely critical in the determination of threshold distance.

The type of exposure considered during earlier test plans was primarily that of an aircraft at delivery time on a typical Strategic Air Command (SAC) mission. Protective requirements for this type of mission have been superseded by the more-critical requirements for flashblindness protection of Tactical Air Command (TAC) and Air Defense Command (ADC), i. e., an ADC mission requiring protection from their own or enemy countermeasure weapons, a TAC mission requiring protection from weapons dropped unexpectedly by allied aircraft, as well as the SAC mission requiring protection from enemy countermeasures. The critical requirements of TAC and ADC made a renewal of effort in this field mandatory.

The original decision to proceed with feasibility studies and subsequent development contracts for flashblindness protective devices was made as a result of a conference composed of USAF and industry representatives held at Headquarters, Air Research and Development Command (ARDC), Baltimore, Maryland, on 18 and 19 January 1955.

There had been three pertinent contracts. Two were feasibility studies to investigate the applicability of the Kerr cell principle. One contract was with Baird Atomic, Cambridge, Massachusetts, and the other with CBS Laboratories, New York. The third contract, with Electronics Corporation of America, provided for development of an electromechanical shutter. The electromechanical shutter was the only self-actuating protective device which was ready for field testing during this operation.

1.3 THEORY

Three factors contribute to the relative scotoma and lowering of visual acuity during and following exposure of the eye to high-intensity light. These are glare from the light source, bleaching of the visual pigment with the resultant time interval necessary for readaptation, and after images. Because of the interrelationship of the above three factors, the effects of intense stimuli are complicated and difficult to estimate.

1.3.1 Glare. Glare was defined (Reference 4) as any degree of light falling upon the retina in excess of that which enables one to see clearly; that is to say, any excess of light which hinders instead of helps vision. Glare is differentiated into: (1) veiling glare, created by light uniformly superimposed on the retinal image which reduces contrast and therefore visibility; (2) dazzling glare, adventitious light scattered in the ocular media so as not to form part of the retinal image; and (3) scotomatic (blinding) glare, produced by light of sufficient intensity to reduce the sensitivity of the retina and corresponding to a heavy overexposure in photography (Reference 5).

Although all three types of glare are present in the case of high-intensity light, the effects of the first two are primarily evident only while the source is present. The third type is especially significant because it gives rise to those symptoms which persist long after the light source itself has vanished.

1.3.2 Adaptation. A change produced in a retinal area which can be traced to the after effects of previous stimulation is termed adaptation. When the eye becomes attuned to bright light, it is said to be light adapted; when it is attuned to low levels of illumination, it is said to be dark adapted. Vision in these two states shows fundamental differences. The change from one state to another is not instantaneous. Instead, a definite time interval, depending on the direction and extent of change in adaptation desired is required. Readaptation times to a previous level of adaptation after expo-

sure to the intense light of the magnitude with which this report is concerned are not adequately defined.

Adaptation of the retina after exposure to white light varies considerably with the area of the retina considered. The sensitivity of the peripheral retina may be increased from 50,000 to 100,000 times and requires at least 30 minutes before full adaptation is approached. The increase in sensitivity of the fovea (central retina) with dark adaptation is relatively small, compared with that of the peripheral retina. The increase in foveal sensitivity with dark adaptation is only 10 to 20 times that of the light-adapted fovea and the time interval required for adaptation is 5 to 8 minutes.

Fortunately, the pilot exposed to intense light need only recover useful foveal vision. Useful vision in this case is the ability to read aircraft instruments necessary in continuing the mission.

Available laboratory studies give only a meager indication of the time required to recover this useful vision after exposure to the intensity of light being considered here. Lohman (Reference 5) has shown that foveal dark adaptation is lost with extreme rapidity on exposure to bright light. Foveal readaptation to low levels of illumination is known to be relatively fast. Use of high-intensity instrument lighting will decrease the time interval between exposure of the eye to a flash of light and the return of the useful vision. A report by Fry (Reference 6) indicated that retinal readaptation after exposure to moderate intensities of light follows a definite pattern, i. e., with short exposures the intensity times the duration equals a constant. In this test of an electromechanical shutter, both duration and intensity of the stimulus are decreased.

1.3.3 After Images. The after image is a prolongation of the physiological processes that produced the original sensation response after cessation of stimulation. If similar in nature to the original sensation, it is called a positive after image. Thus, if a light is fixated for a time and then turned off, an image can still be seen. Ordinarily, the sequence of events following stimulation of the retina by a flash of light is the primary sensation of light followed by a series of positive and negative after images. With moderate light intensities, after images are not noticed because of the complex action of successive stimulation and continuous movement of the eyes. However, if the original stimulation is of sufficient duration and intensity, the sensation will persist with an intensity adequate to reduce or entirely obliterate foveal perception until the effect is dissipated. The time relation of recovery from after images has not been satisfactorily elucidated. In general terms, at the fovea, the latent period varies inversely, and the duration of the after image varies directly with the duration of the primary stimulus up to a limit of fixation of 1 minute.

1.4 GLOSSARY

nyctometer: an instrument designed to measure central visual acuity under controlled levels of background brightness.

scotoma: a blind area in the visual field. It may be temporary or permanent.

stereocampimeter: an instrument designed to map out the sensitivity of the central area of vision.

fovea: the central, most sensitive area of the eye, capable of acute vision.

modal point: that point in the eye through which all incoming rays pass.

Chapter 2
PROCEDURE

Two identical experimental test beds were used on three of the five participations. One test bed was in a C-47 aircraft and the other in a trailer (Figures 2.1 and 2.2). Site locations and distances from ground zero are indicated in Table 2.1. Each station had arrangements for six subjects. These included six portholes with facilities for mounting four shutters (Figures 2.3 and 2.4). In addition, at least one window at each site was replaced with a sandblasted diffusing screen to simulate the exposure to the illumination of a nuclear detonation that might be received by an aircrew while flying above, below, or within a cloud layer (Figure 2.5). An examiner was present for each subject. Actual number of positions occupied varied from two to five. Thus, two to five subjects, plus examiners, were present at each station for three of the five participations. Voice countdown was received in both the airplane and trailer by radio. Each subject observed the detonation from his assigned position.
cated slightly to the side of his position. Visual recovery was tested on either the stereocampimeters, nyctometers, and aircraft instruments, or a combination (Figures 2.6 and 2.5). Times to recover useful vision, as measured by the ability to read aircraft instruments, and the return of mesopic visual acuity, as measured on the nyctometer, were determined and recorded.

Four or more rabbits were also exposed as controls at each location. Each animal was placed in a holder designed to minimize movement and insure proper positioning for exposure.

Upon completion of visual-recovery testing, all personnel were returned to Nellis AFB for complete ophthalmological evaluation. This included visual fields, visual acuity, ophthalmoscopy, and retinal photography.

2.1 SHOT PARTICIPATION

The prototype shutters tested were intended primarily for tactical use. For planning purposes, any of the scheduled events were satisfactory from a yield standpoint. Predawn detonations were preferred. Actual participation with pertinent related information is indicated in Table 2.1.

2.2 INSTRUMENTATION

In order to fully evaluate the effectiveness of the shutter, it was necessary to obtain absolute thermal and photometric data as a function of time. Times of special interest were 0.5 msec and 100 msec, corresponding to the average shutter closure time and the normal human blink time, respectively. Figure 2.7 illustrates schematically the instrumentation and recording layout at each site.

2.2.1 Thermal and Photometric Instrumentation. It was necessary to instrument both the ground station and the C-47 aircraft station with more-sensitive instruments than the standard Naval Radiological Defense Laboratory (NRDL) MK-6F instruments

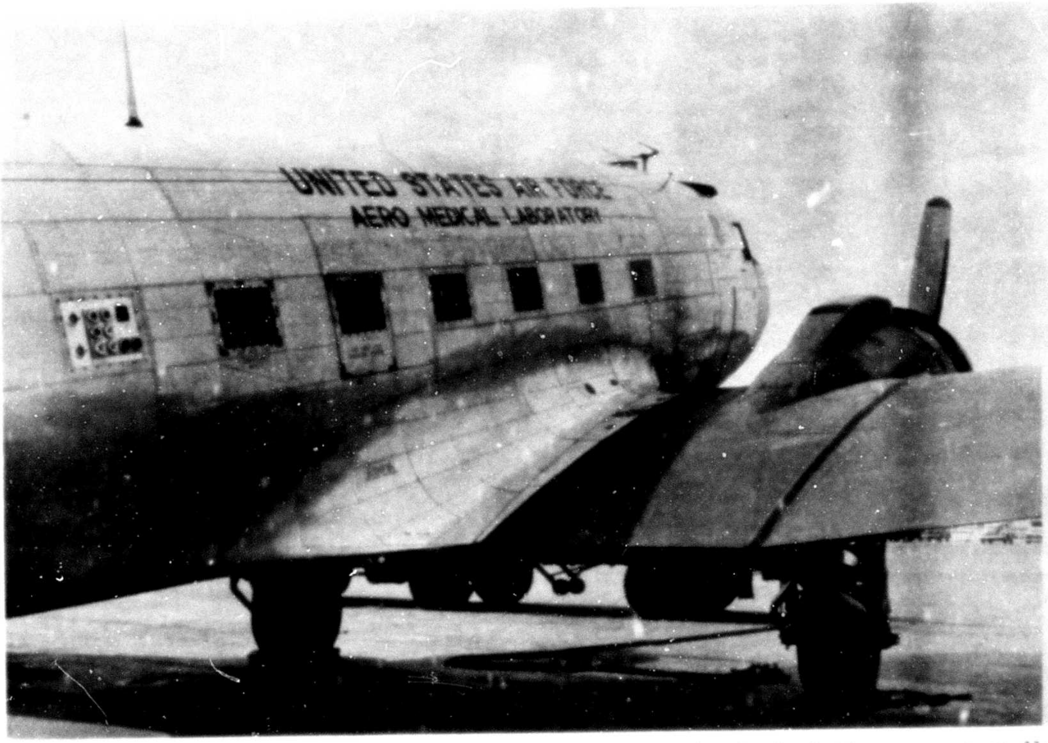

Figure 2.1 Project 4.2 aircraft exterior. Electromechanical shutters are installed on the forward four windows. The fifth window is unobstructed. The sixth window has been replaced with a sandblasted diffusing screen and the seventh window has been replaced with the aircraft-instrument holder.

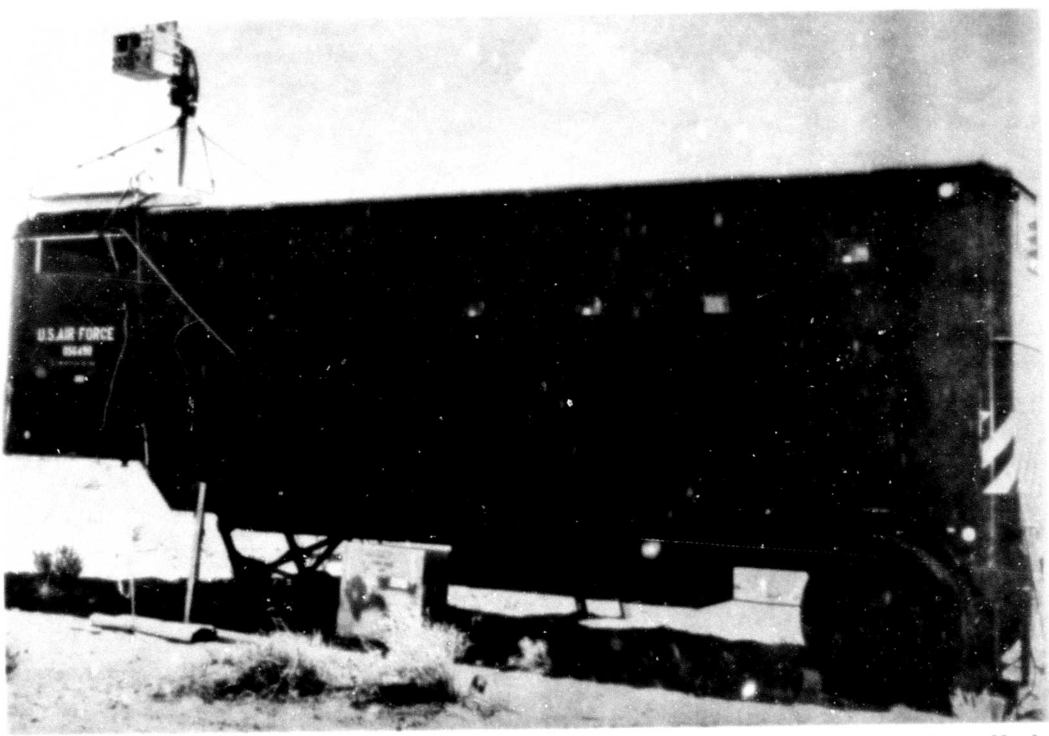

Figure 2.2 Project 4.2 trailer exterior. Electromechanical shutters are installed in four portholes, diffusing screen in the fifth, and a fiducial marker in the sixth. Trailer-instrument holder is mounted on top.

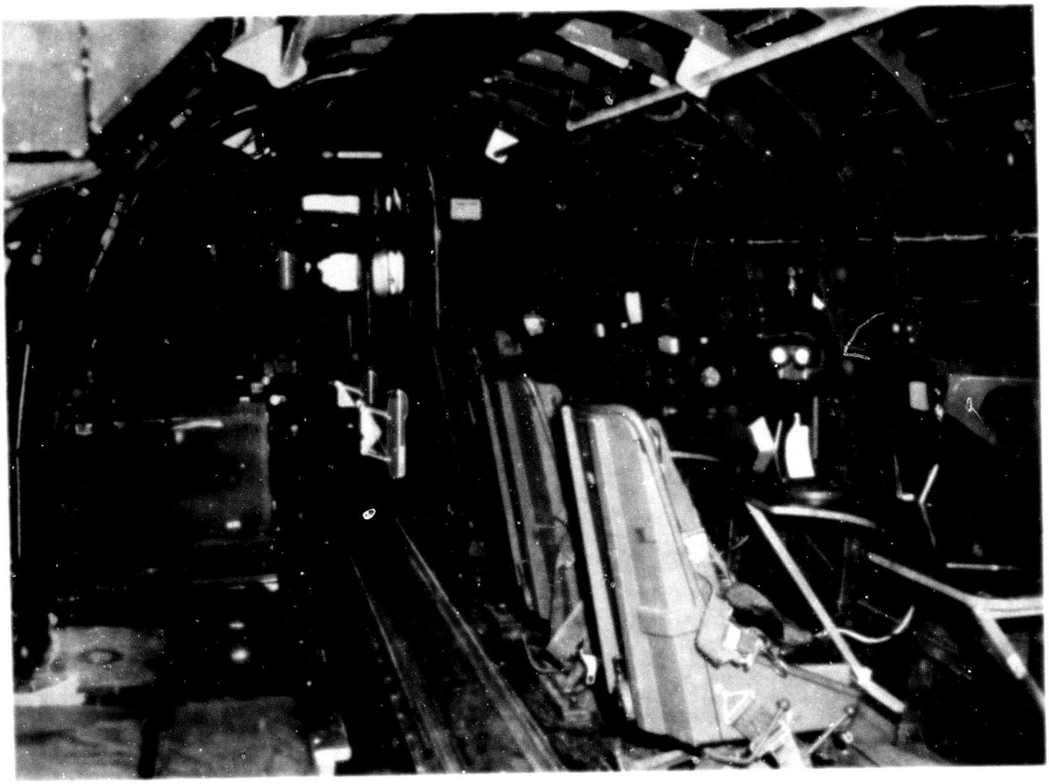

Figure 2.3 Aircraft interior. Visual-recovery instrumentation shown on the right. Oscilloscopes for recording shutter closure times are on the left.

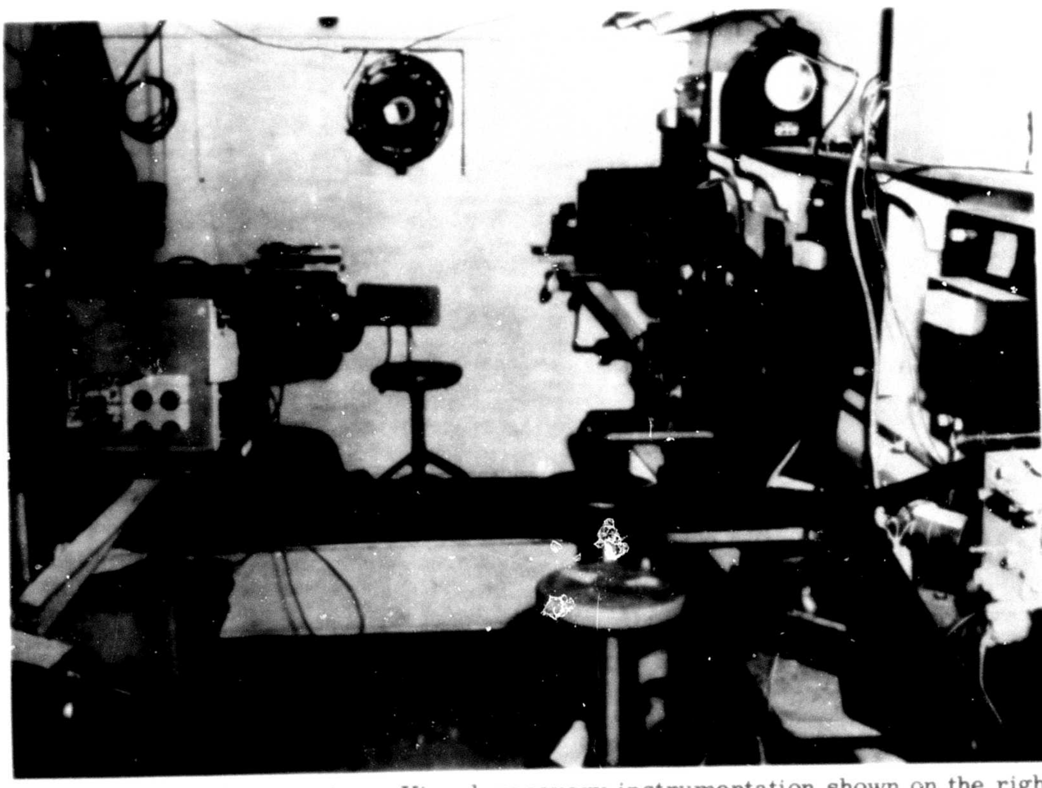

Figure 2.4 Trailer interior. Visual-recovery instrumentation shown on the right. Oscilloscopes for recording shutter-closure times are on the left.

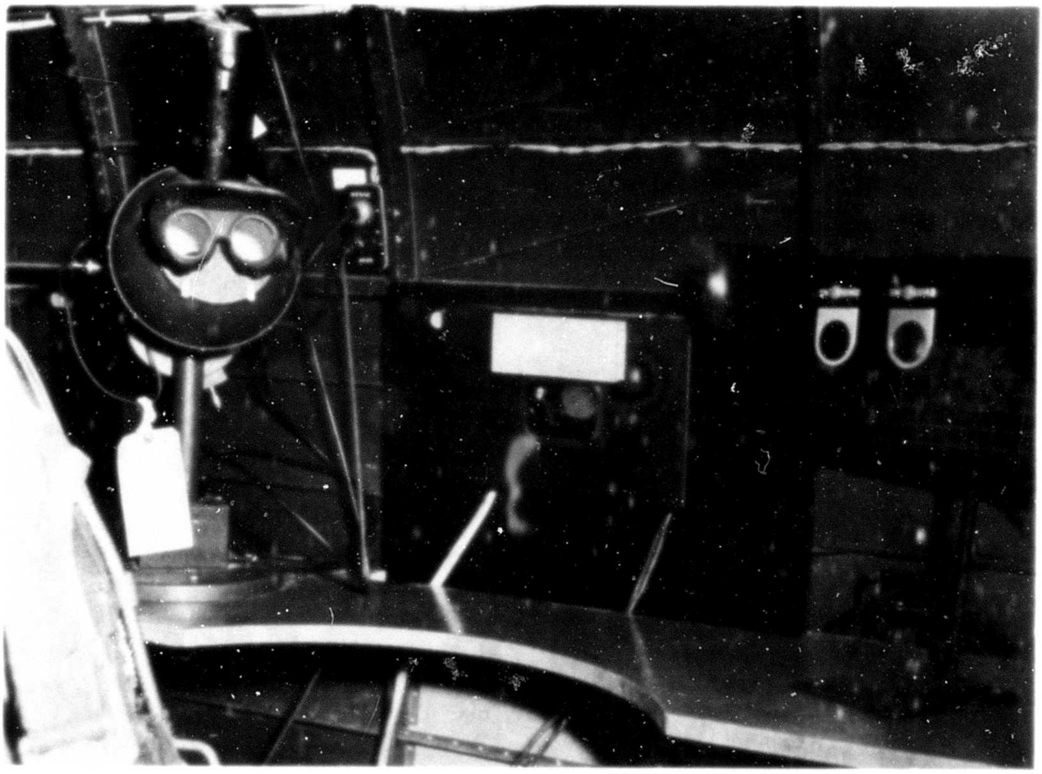

Figure 2.5 Typical antiglare shutter and visual-recovery instrumentation arrangement, showing the nyctometer on the left of the shutter with the stereocampimeter on the right.

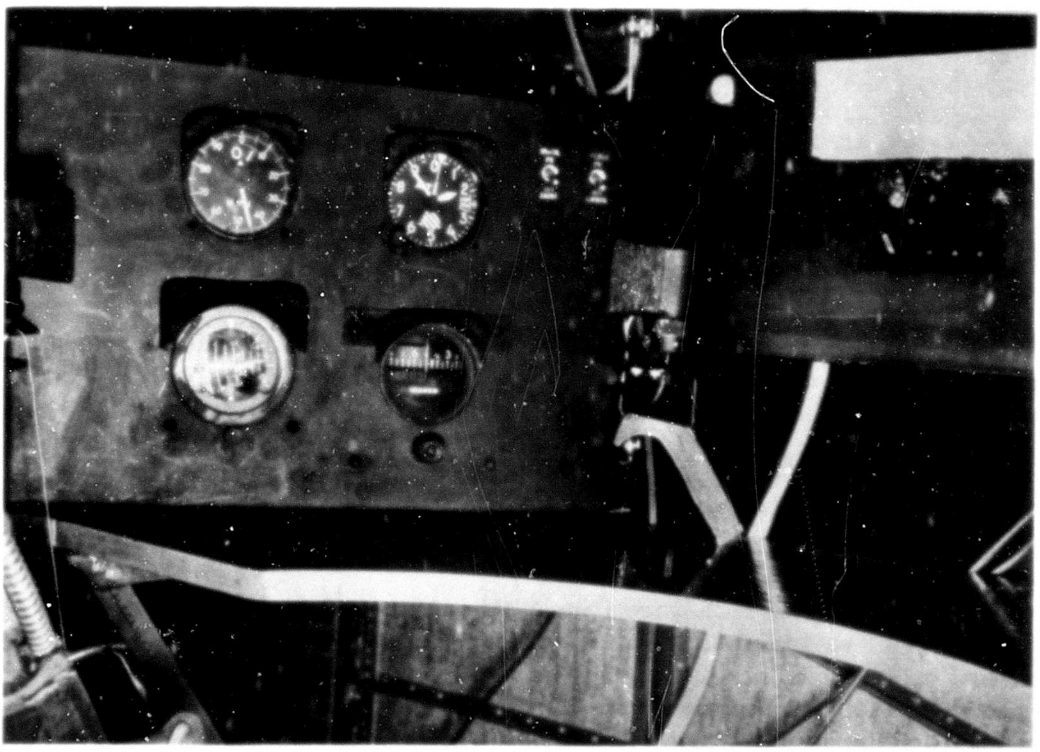

Figure 2.6 Typical antiglare shutter and visual-recovery instrumentation arrangement, showing aircraft instruments on the left.

(Reference 7), since both stations were positioned to receive an estimated total thermal energy of between 0.04 to 0.1 cal/cm^2. An instrument holder was designed and installed by NRDL personnel. Two multijunction calorimeters were used in conjunction with Heiland oscillographic recorders. In all cases where thermal radiation instruments were used, gun-sight-aiming-point (GSAP) cameras were mounted adjacent to these instruments. These cameras were used to provide information regarding the orientation of the thermal instruments with respect to line of sight. The GSAP cameras were modified so that a cam mounted on the shutter closed a microswitch every fifth

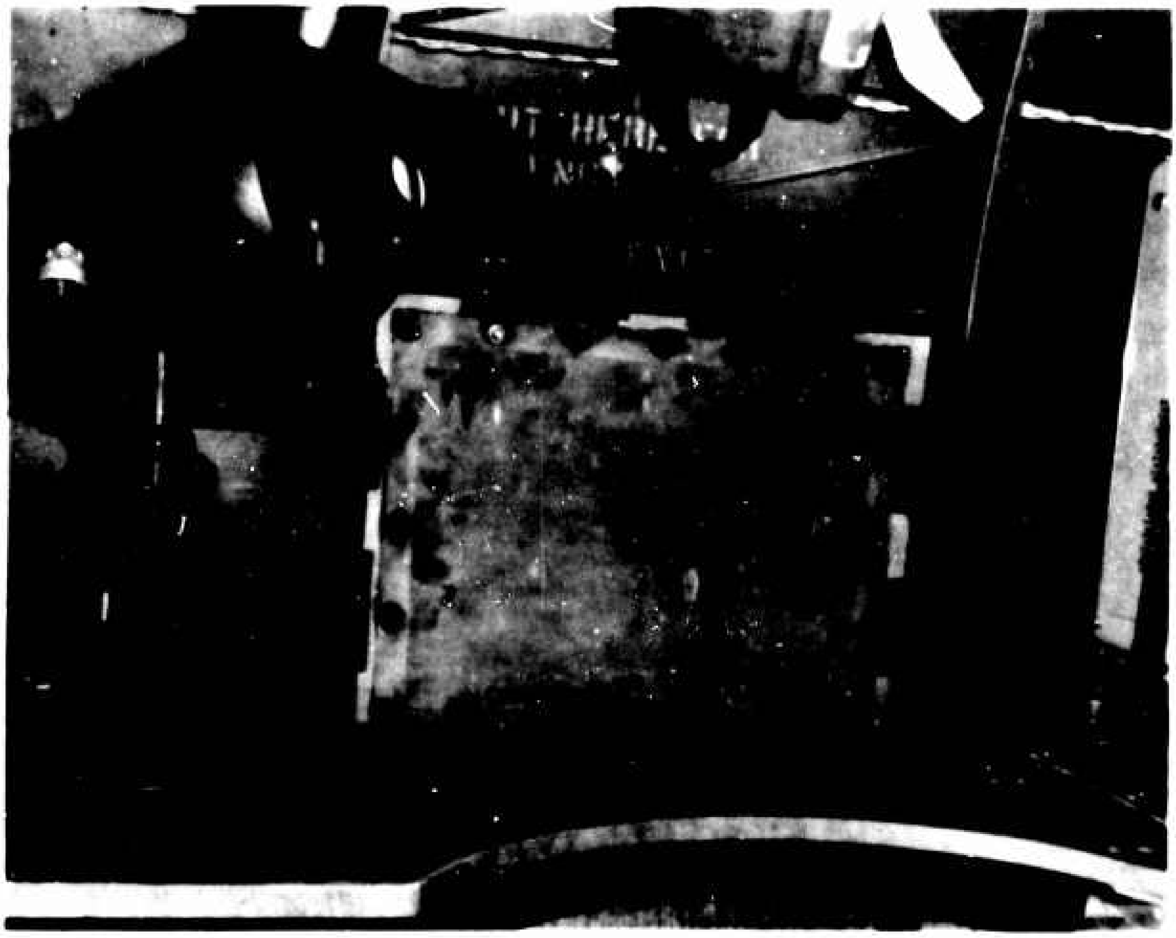

Figure 2.7 Diffusing-screen exposure station with nyctometer on the left.

frame. A battery and a resistor completed a circuit to a Heiland galvanometer to give an indication of the time from time zero of each frame.

All the thermal instruments were calibrated at NRDL prior to the operation by exposure to the Mitchell high-intensity thermal-radiation source (Reference 8), by the use of techniques identical to those described elsewhere (Reference 9). Several series of calibration runs were made prior to shipment of the instruments to the NTS. The procedure provided for recalibration of the instruments on the same source upon their return to NRDL.

The electrical calibrations were accomplished by introducing standard millivolt signals in series with the final field circuits a few hours before scheduled shot time. Electrical calibrations were checked in the same way after each shot. The photocells and phototubes with the associated recording devices (Heiland recorder and oscilloscope) were calibrated as a unit. Because of the difficulty in maintaining and assuring stability of a standard lamp under field conditions, a Weston photometer was carefully calibrated under laboratory conditions prior to project departure for the NTS to be

used in determining the light incident on the detectors during each calibration. A 500-watt projection bulb was used as a light source. This source was placed at ten or more positions for each calibration, and the light levels, as indicated on the photometer, were recorded. Two base lines with the photocells completely covered were also established at each calibration run. Deflection at each light level, as indicated on the oscilloscope, was recorded. Deflection recorded on oscillograph paper was measured to within 1/1,000 inch on reading equipment operated by NRDL.

The special thermal instruments required at the ground site for the anticipated low thermal energies involved were similar to the instruments used on the B-36 drop aircraft for Shot 10 of Operation Teapot.

Six instruments were 20-junction calorimeters. These consisted of 20 blackened buttons 0.25 inch in diameter and 10 mils thick. Each button had a copper-constantan

TABLE 2.1 PROJECT 4.2 PARTICIPATION

Shot	Yield	Distance to Site	
		Air	Ground
	kt	yds	yds
Boltzmann	11.5 ± 0.8	21,200	17,600
Wilson	10.3 ± 5 pct	19,360	15,136
Priscilla	36.6 ± 1	30,400	20,649
Hood	74.1 ± 5 pct	32,426	—
Diablo	18.7 ± 1.5	—	18,304

thermocouple soldered to the back with the thermocouples connected in series to the recorder. The whole assembly was contained in a standard MK-6F instrument case. This particular instrument had a sensitivity of about 0.02 (cal/cm^2) mv and a decay rate of about 30 percent/sec.

Two instruments were used to measure the incident light flux with nearly the same spectral sensitivity as the eye. They were Weston Photronic photoelectric cells, Type RRV, used in conjunction with Kodak neutral-density gelatin filters. Their outputs were recorded by Heiland 350-105 galvanometers on the Heiland oscillograph recorder. These photocells were also adapted to a standard MK-6F instrument case.

One instrument was designed to measure short-time illumination. The receiver in this case was an RCA-934 phototube used in conjunction with a Corning 3389 filter, a Kodak 106 Wratter filter, and a suitable Kodak neutral-density filter. This combination of phototube and filters coincided with the spectral sensitivity of the eye. The whole assembly was mounted in a minibox, and the output of this instrument was recorded on a Dumont 333, or Tektronix 532, oscilloscope.

Application of the appropriate calibration factors and the making of corrections for the decay rate of heat loss in the case of the calorimeters led directly to values of the thermal energy. All the instruments described were contained in two standard instrument holders and were oriented in the direction of the fireball. One Model 500B Heiland oscillographic recorder was used to record the signals.

Instrumentation used on the C-47 airplane was similar to that used on the ground station, with the exception that more-sensitive calorimeters were used to record part of the incident thermal energy: (1) three special 20-junction calorimeters, similar to

those described above, were used to measure thermal radiant energy; (2) three of these sensitive instruments were 10-junction Minneapolis-Honeywell thermopiles. These were mounted in Standard MK-6F instrument cases and had a sensitivity of about 0.0002 (cal/cm^2)/mv. The decay rate of heat loss was about 260 percent/sec.; (3) two Weston Photronic photoelectric cells, Type RRV, as described above, were used to measure the incident light flux; and (4) one RCA-934 phototube, as described above, was used to measure short-time illumination.

All the instruments described were mounted on a metal plate which was mounted in a window frame of the aircraft. One Heiland Model 500B oscillographic recorder was provided to record the signals.

Figures 2.8 and 2.9 are schematic layouts showing the positions of the various instruments in the holders at the two sites. Tables 2.2 and 2.3 give details regarding

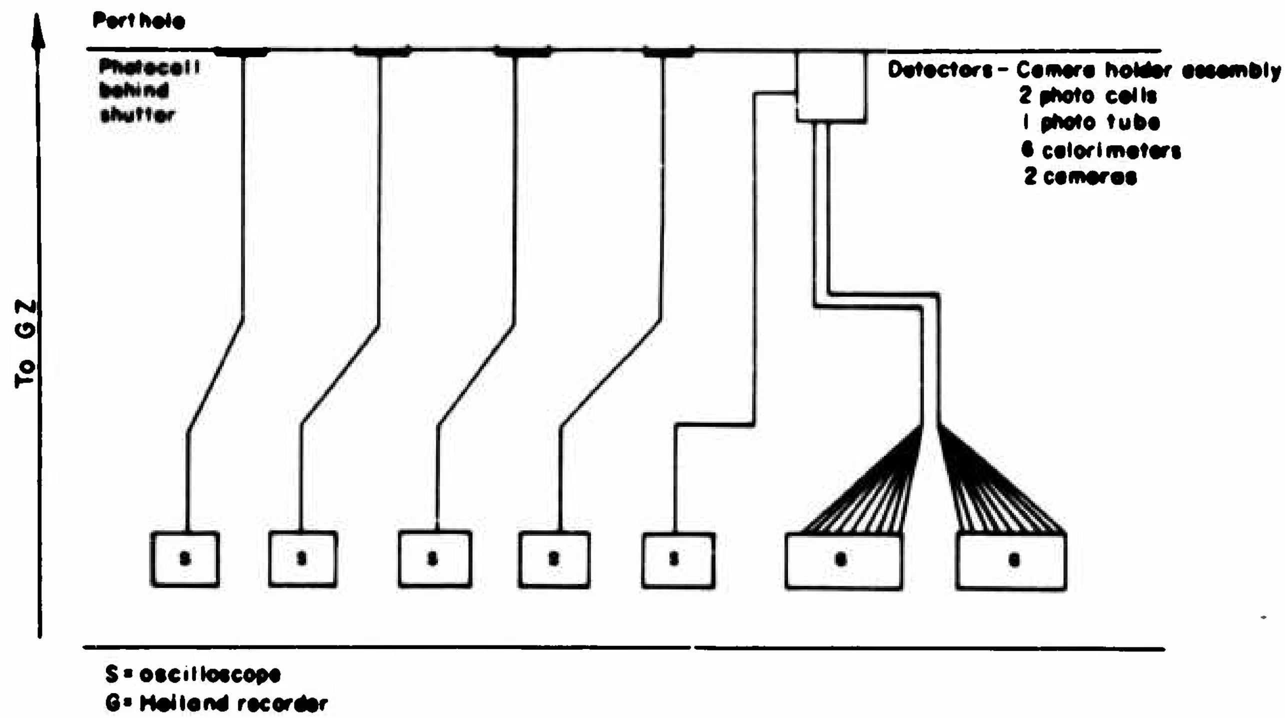

Figure 2.8 Schematic instrument layout.

the individual instruments. Column 1 refers to instrument positions as given in Figures 2.8 and 2.9. The meaning of Columns 2 and 3 is self-evident. Column 4 gives the filter designations. The letter Q refers to a quartz filter, while 0-52, 3-69, 2-58 and 3-75 refer to Corning glass filters.

2.2.2 Visual-Recovery Instrumentation. Four German-manufactured nyctometers were utilized to test mesopic visual acuity (Figure 2.6). Background brightnesses of 0.125, 0.5, 4 and 32 apostilbs were available. Times to recover 0.1, 0.3, and 0.5 acuity were recorded. During this test, the background brightness was maintained at 4 apostilbs (0.37 ft-L). Background brightness was measured and the nyctometer calibrated in the laboratory prior to the beginning of the operation by the use of a Spectra-Spot photometer. Brightness was rechecked prior to each event.

Return of useful vision was determined by the ability of the individual to read correctly four aircraft instruments: altimeter, air-speed indicator, gyro compass, and artificial horizon (Figure 2.10). Each instrument was illuminated with standard Grimes edge lighting, as well as standard red flood-lighting. Stereocampimeters were available for use when indicated to determine size of the visual scotoma (Figure 2.6).

2.2.3 Antiglare Shutter. The electromechanical shutter tested was an experimental model developed under USAF contract and consisted of a shutter assembly, flash detector, and a power supply (Figure 2.11).

The shutters consisted of a pair of movable glass plates, each inscribed with a series of alternately opaque and transparent lines. When the shutters were open, the transparent lines of one plate were superimposed over the transparent lines of the other plate. The lines were narrower than the pupillary width. Therefore, there were no blind areas in the field of vision, and the net effect was that of a neutral-density filter. Total light transmitted through the shutter was approximately 20 percent for

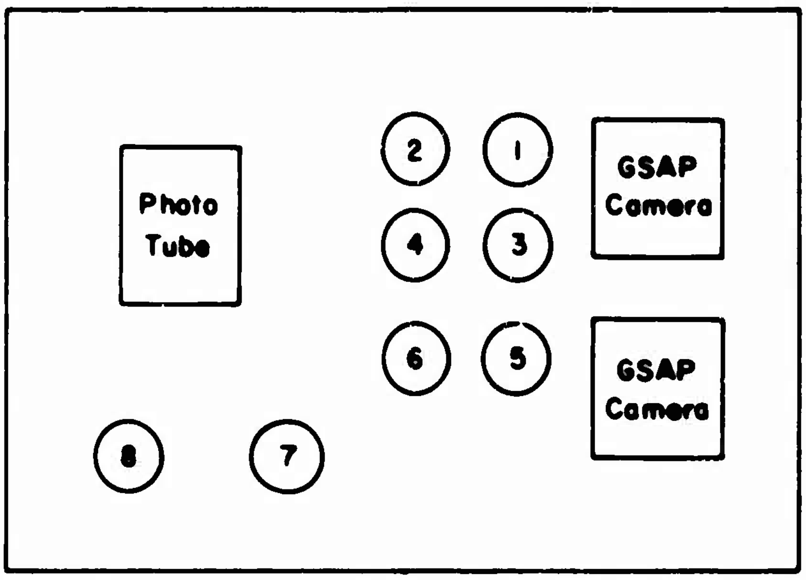

Figure 2.9 Aircraft instrumentation holder.

field test units. Each plate was held in position by a fine actuating wire which restrained a spring.

When the flash detector sensed the presence of unusual illumination considerably above a preset level, it produced a signal that discharged a capacitor in the power supply. The current thus released passed through the wires, heating them and causing them to expand. As a result, each grid was moved one half opacity width by its spring (one to the right, the other to the left) so that opaque lines of one grid were now aligned with transparent lines of the other, effectively cutting off all light to the subject's eye. Another circuit held the shutters closed for a short preset interval; then the wires cooled and contracted, pulling the grids back to their original open position, so that the subject could see again.

The actuating eye (flash detector) of the antiglare shutter system was a light-sensitive detector (PbS cell) which reacted to changes in the ambient light level. This cell was mounted in a small housing fastened inside the window of the test bed and in front of the shutter. As the radiation striking the cell increased, the cell resistance decreased. The resulting rise in voltage across the associated 820-k cell load resistor was capacitance-coupled to the related cathode follower. The signal from the cell through the cathode load resistor was applied to the trigger amplifiers in the power supply.

The power supply was not triggered from small or gradual changes in light level; the flash intensity and rate of increase had to exceed a minimum level, established by the time constants of the coupling circuits and the trigger thresholds of the power supply.

TABLE 2.2 THERMAL INSTRUMENTATION ON TRAILER GROUND STATION

Instrument Position	Instrument Number	Instrument Type	Filter	Filter Transmission, Microns
1	XX-7	20 Junction	Q	0.22-4.3
2	XX-13	20 Junction	Q	0.22-4.3
3	XX-12	20 Junction	0-52	0.358-3.25
4	MH-9	10 Junction	3-69	0.527-2.75
5	MH-7	10 Junction	2-58	0.64-2.75
6	MH-5	10 Junction	3-75	0.398-2.75
11	PC-RRV-3*	Photocell	ND-2	—
12	PC-RRV-5	Photocell	ND-3	—
—	RCA-934	Phototube	Corning 3389	—
—	—	—	Kodak 106 Wrattan	—
—	—	—	Kodak Neutral Density	—

* Replaced by PC-RRV-2 for Shots Priscilla and Hood.

TABLE 2.3 THERMAL INSTRUMENTATION ON C-47 AIRPLANE STATION

Instrument Position	Instrument Number	Instrument Type	Filter	Filter Transmission, Microns
1	XX-27	20 Junction	Q	0.22-4.3
2	XX-32	20 Junction	Q	0.22-4.3
3	XX-25	20 Junction	0-52	0.358-3.25
4	XX-29	20 Junction	3-69	0.527-2.75
5	XX-24	20 Junction	2-58	0.64-2.75
6	XX-26	20 Junction	3-75	0.398-2.75
7	PC-RRV-6	Photocell	ND-2	—
8	PC-RRV-7	Photocell	ND-2	—
–	RCA-934	Phototube	Corning 3389	—
–	—	—	Kodak 106 Wrattan	—
–	—	—	Kodak Neutral Density	—

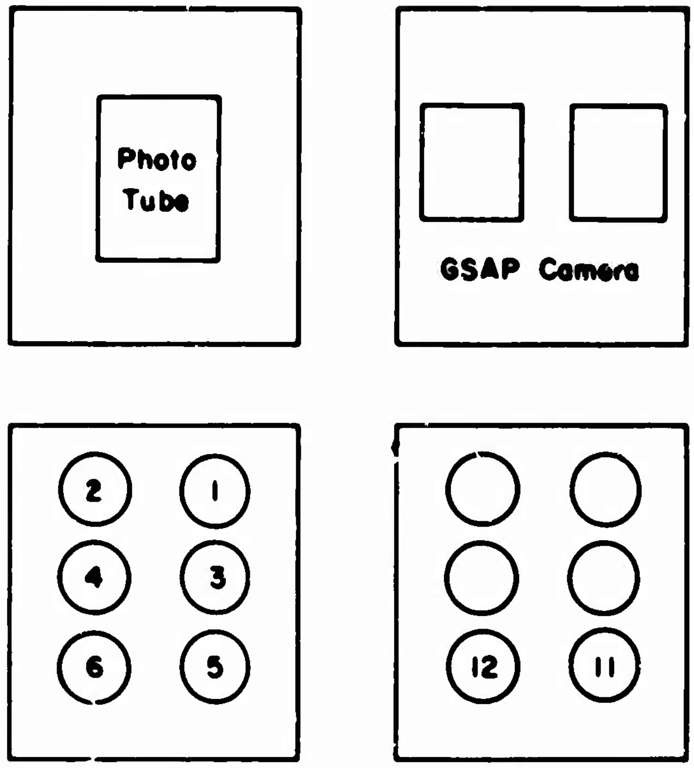

Figure 2.10 Trailer instrumentation holder.

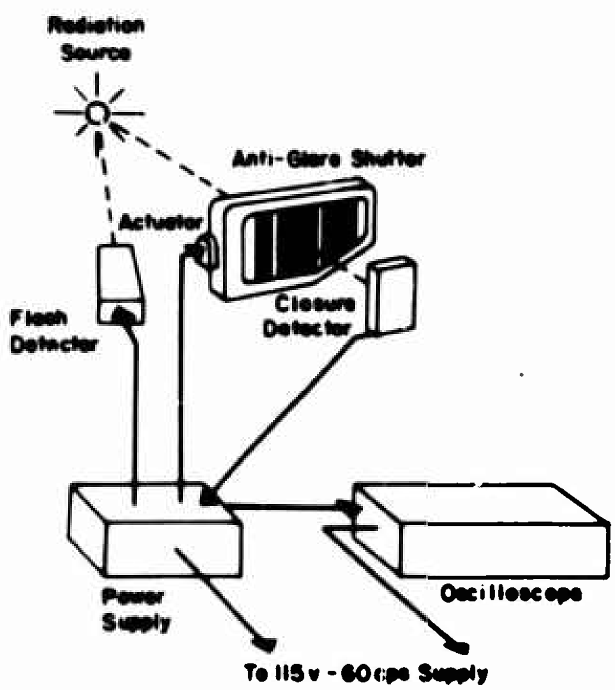

Figure 2.11 Antiglare shutter system.

The actuator power supply performed three functions: (1) on a signal from the detector, it produced a current surge to heat the shutter-actuator wires for rapid expansion; (2) it furnished a hold current to keep the actuator wires expanded for a safe period following the initiation of the flash, and (3) it furnished B+ and filament voltage to the actuator-detector.

Closure time of the shutter was measured by a photocell behind the shutter grids.

2.3 SITE LOCATION

On the basis of past field tests and the work described in References 10 and 11, a safe critical chorioretinal burn threshold was taken as 0.004 calorie incident at the cornea delivered over the first 0 1 second, or a thermal irradiance at the retina of 80 (cal/cm^2)/sec. This assumed a pupillary opening of 8 mm, ocular transmission of 78 percent, and a retinal image size of 0.15 mm. Accordingly, each site was located such that in the event of a shutter failure, no more than 0.004 calorie would be obtained over the first 0.1 second (human blink time). Distances from ground zero for the shot participations are given in Table 2.1.

A more conservative figure was used for added safety on Shot Hood, during which shutters were intentionally rendered inoperative. Atmospheric transmission was assumed, on the basis of past experience, to be 95 percent per statute mile for the ground station and 96 percent/mile for the air station.

Chapter 3
RESULTS

3.1 SHUTTER CLOSURE EVALUATION

All closure times were within 550 ± 50 μsec, except for three cases where shutters failed to operate (as indicated by the trace record, as well as visual inspection). The shutter malfunctions that did occur were apparent prior to detonation and therefore were not utilized for human subjects.

3.2 VISUAL RECOVERY DATA

Human subjects viewed the detonation through the shutters during four shots. All shutters were operative, and visual recovery was instantaneous in all cases for Shot Wilson, as indicated in Table 3.1.

Three shutters were intentionally rendered inoperative for Shot Hood. One shutter was maintained in an operative condition. Recovery times are as indicated in Table 3.2. Two additional subjects (WEG and CEB) were exposed without protection to Shot Hood behind a sandblasted aircraft window to prevent primary image formation. Recovery time in both cases was approximately 90 seconds before return of 0.1 acuity.

Six human subjects were exposed to Shot Diablo. Recovery times for the four subjects exposed behind shutters are indicated in Table 3.3. Two shutters were operative with a closure time of 550 ± 50 μsec. Visual recovery in both cases was instantaneous. Visual recovery for the single subject behind the shutter that closed in approximately 900 μsec was also instantaneous. The fourth subject was exposed behind an open inoperative shutter, which was in turn behind a sandblasted diffusing window. Visual recovery in this case was recorded as 6 seconds for reading standard red-lighted aircraft instruments. A fifth subject (RDM) was exposed without protection behind a sandblasted diffusing window. Visual recovery in this case was 20 seconds for 0.1 acuity, 28 seconds for 0.3 acuity and 35 seconds for 0.5 acuity. A sixth subject (WEG) was exposed with a narrow-band interference filter with approximately 20 percent transmission. No significant or measurable after-effect was noted.

3.3 THERMAL AND PHOTOMETRIC DATA

Total incident thermal energy as received at each site for each participation is given in Table 3.4. The total energy values given in Table 3.4 are the average of the two instruments with quartz filters; these values have been corrected for filter loss by dividing the energy incident on the receiver by 0.92. From the GSAP film the line of sight of the thermal instruments to the detonation point varied from 0 degrees 18 minutes on Shot Boltzmann to 6 degrees 46 minutes on Shot Hood. The correction factor for these values is insignificant and was not used. GSAP photographs are included in the Appendix. Total energy values given in Table 3.4 are the average of the two instruments with quartz filters. No ground participation was scheduled for Shot Hood and no air participation was scheduled for Shot Diablo.

Figures 3.1 through 3.8 illustrate thermal energy as a function of time incident at the site for each participation. Each curve represents the energy after correction for

TABLE 3.1 VISUAL RECOVERY DATA, SHOT WILSON

Site Location: Trailer located 15,136 yards from ground zero, aircraft located 19,360 yards from ground zero.

Shutter No. *	Subject	Visual Acuity 0.1	0.3	0.5	Aircraft Instruments	Visual Fields	
		sec	sec	sec	sec	deg	sec
	Trailer						
T-1	GHM	No measurable recovery time noted				No scotoma noted	
T-2	WRC	No measurable recovery time noted				No scotoma noted	
T-3	RLB	No measurable recovery time noted				No scotoma noted	
T-4	RDM	No measurable recovery time noted				No scotoma noted	
	Aircraft						
A-1	GWC	No measurable recovery time noted				No scotoma noted	
A-2	TGR	No measurable recovery time noted				No scotoma noted	
A-3	WEG	No measurable recovery time noted				No scotoma noted	
A-4	JHH	No measurable recovery time noted				No scotoma noted	

* All shutters operated satisfactorily with a closure time of 550 ± 50 μsec.

TABLE 3.2 VISUAL RECOVERY DATA, SHOT HOOD

Site Location: Aircraft located 32,426 yards from ground zero.

Shutter No. *	Subject	Visual Acuity 0.1	0.3	0.5	Aircraft Instruments	Visual Fields	
		sec	sec	sec	sec	deg	sec
A-1	BCO	—	—	—	10	‡	
A-2	KBO	—	—	—	12	‡	
A-3	JWH	72	90	†	—	‡	
A-4	HWR	No measurable recovery time noted				No scotoma noted	

* All shutters were inoperative except A-4 which operated satisfactorily with a closure time of 550 ± 50 μsec.

† Subject's uncorrected visual acuity 20/25.

‡ Visual fields not obtained.

TABLE 3.3 VISUAL RECOVERY DATA, SHOT DIABLO

Site: Trailer located 18,304 yards from ground zero.

Shutter No.	Shutter Closure Time	Subject	Visual Acuity 0.1	0.3	0.5	Aircraft Instruments	Visual Fields	
			sec	sec	sec	sec	deg	sec
T-1	550 ± 50	AJK	No measurable recovery time noted				No scotoma noted	
T-2	900 ± 50	DGM	No measurable recovery time noted				No scotoma noted	
T-3	Inoperative	DTB			6		Not measured	
T-4	500 ± 50	LGD	No measurable recovery time noted				No scotoma noted	

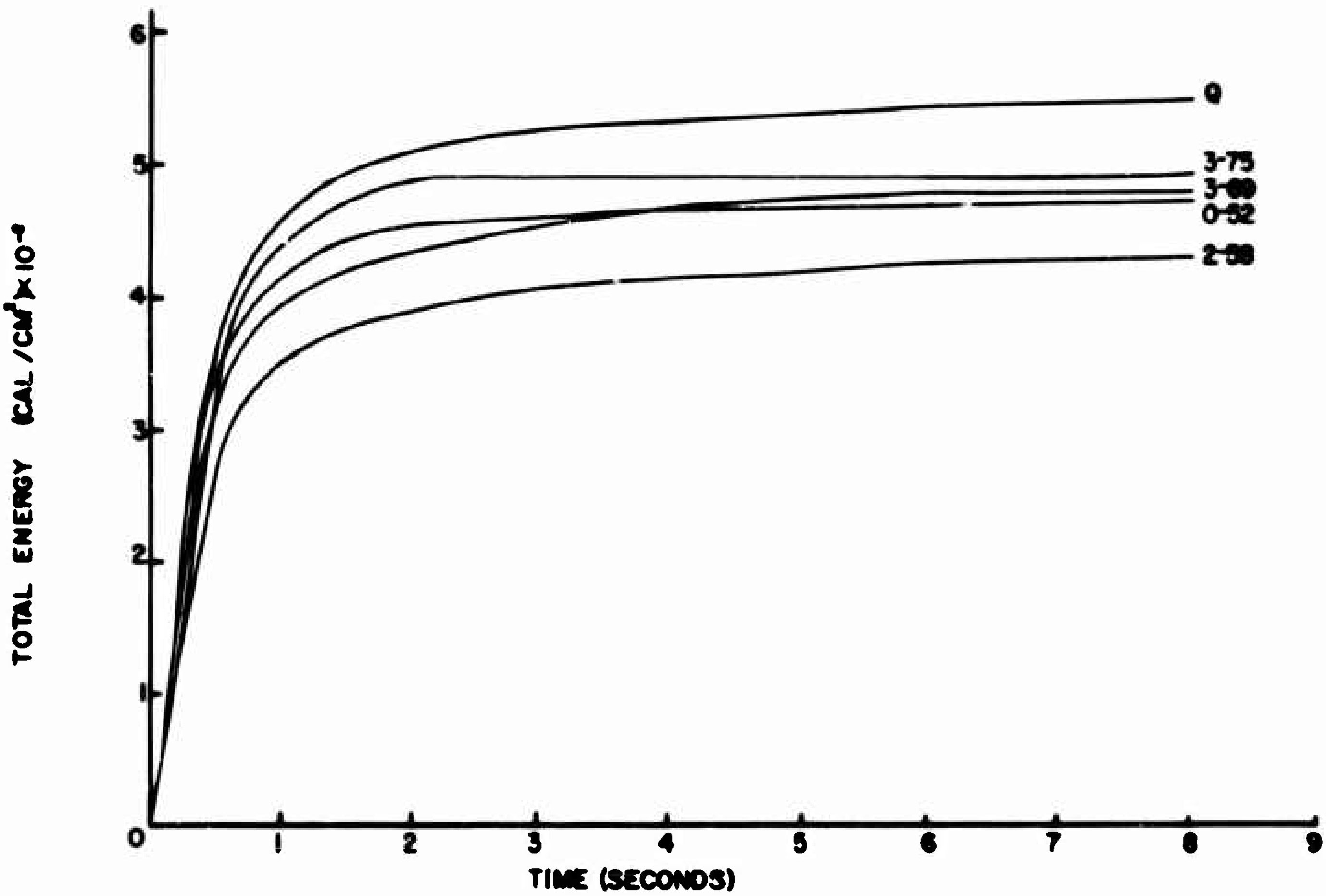

Figure 3.1 Total energy versus time, Shot Boltzman, trailer station.

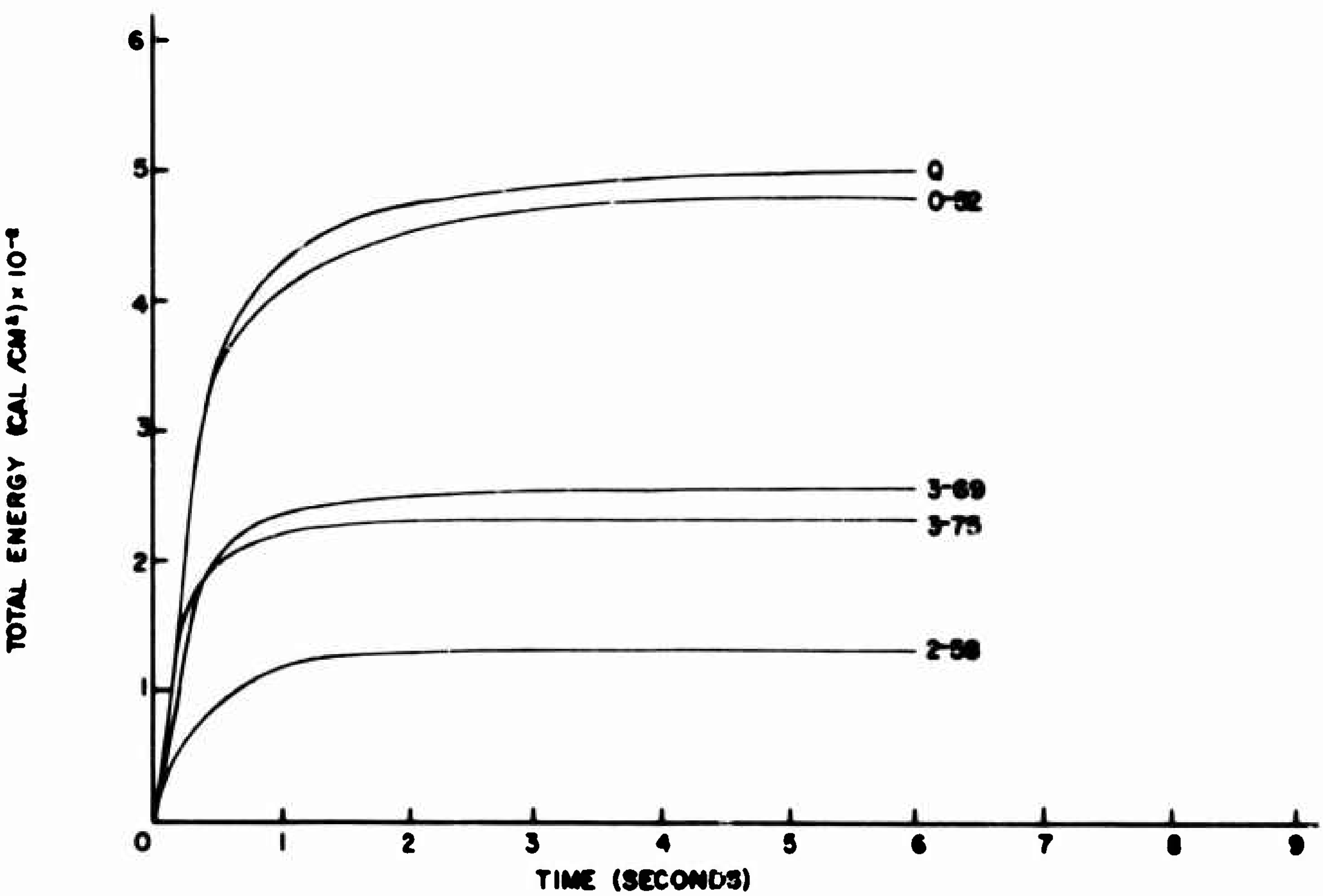

Figure 3.2 Total energy versus time, Shot Boltzmann, C-47 station.

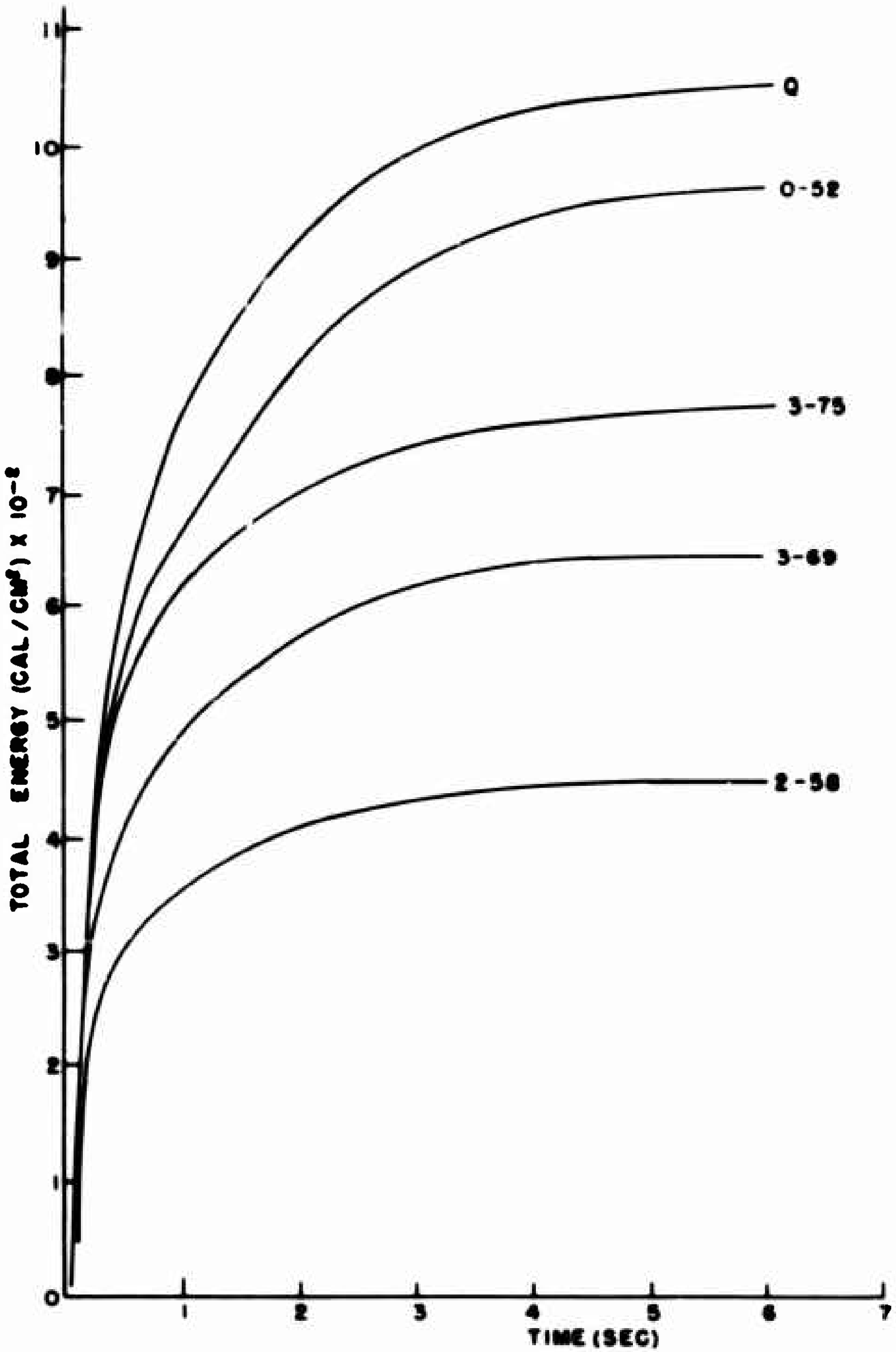

Figure 3.3 Total energy versus time, Shot Wilson, trailer station.

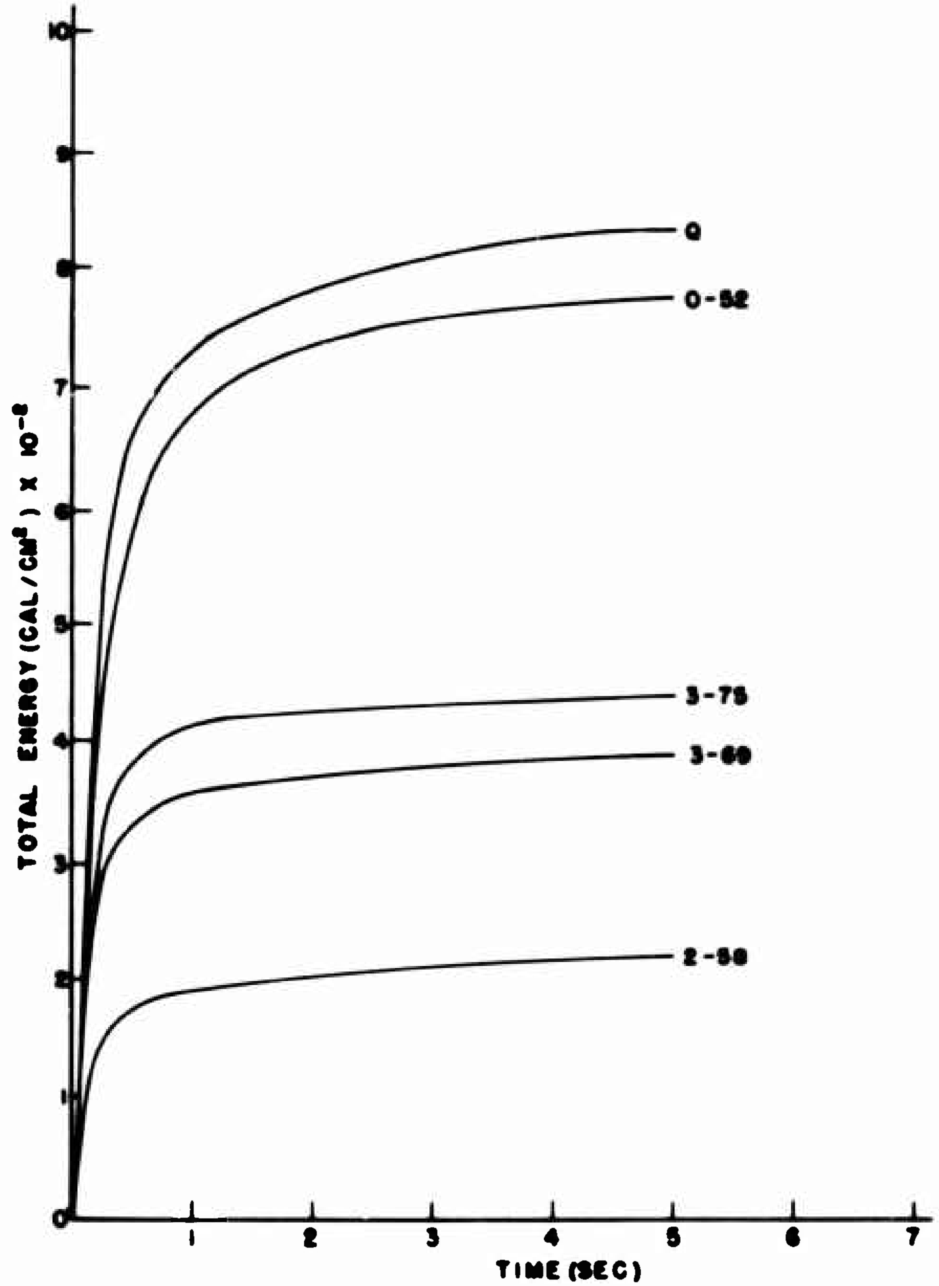

Figure 3.4 Total energy versus time, Shot Wilson, C-47 station.

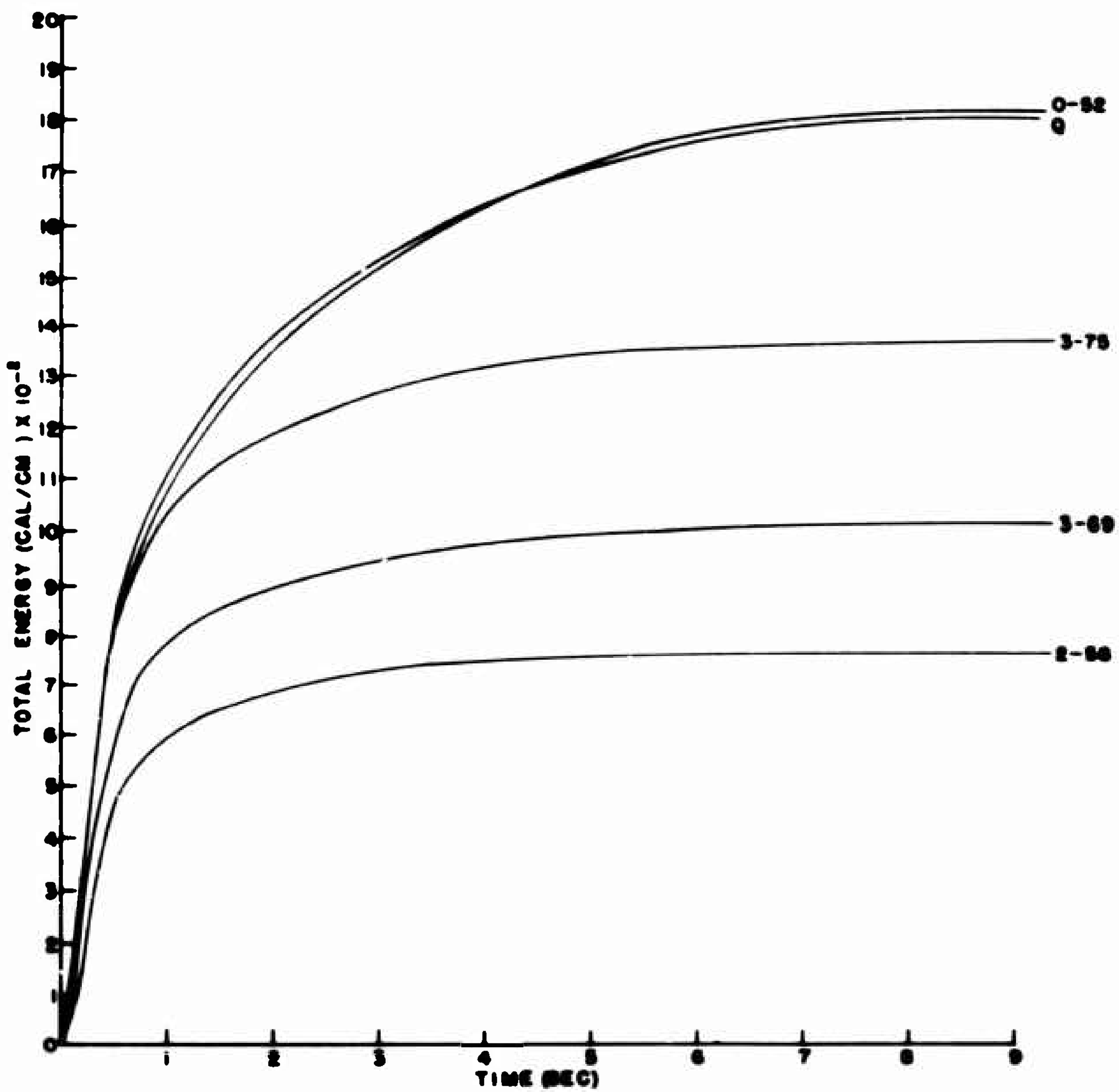

Figure 3.5 Total energy versus time,
Shot Priscilla, trailer station.

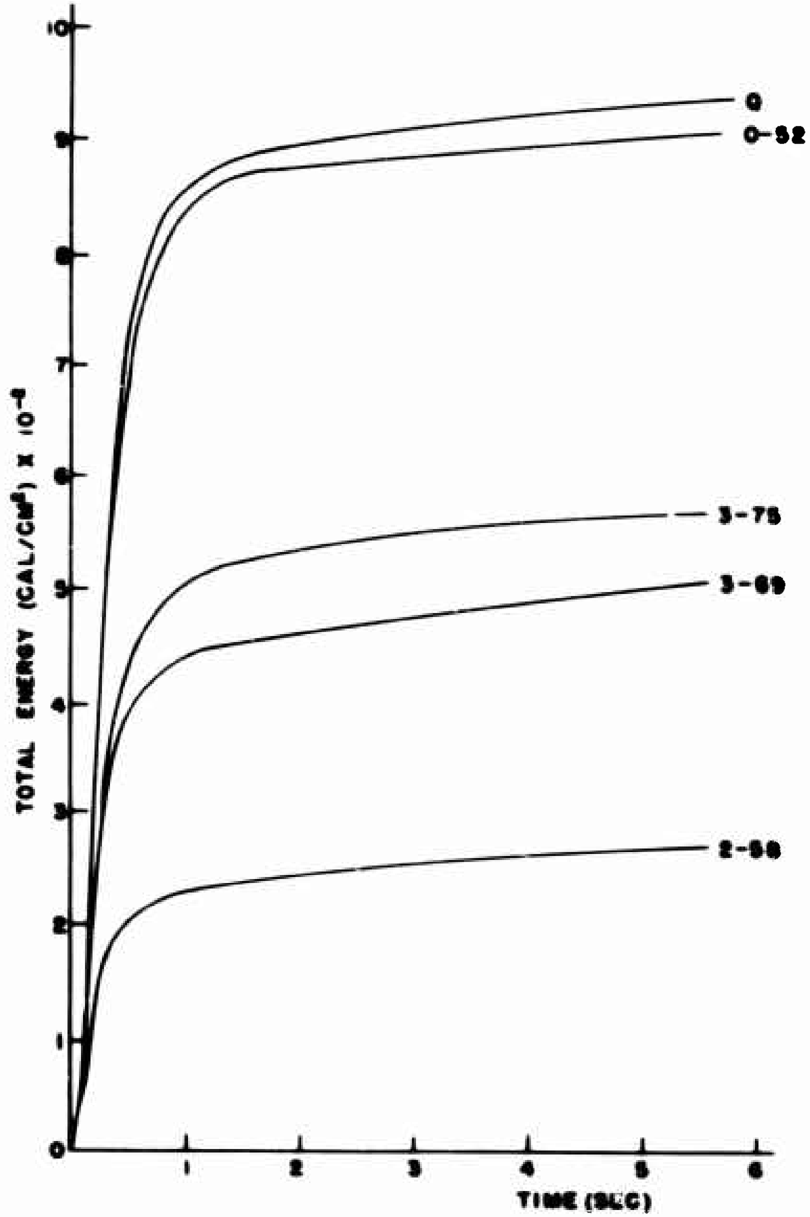

Figure 3.6 Total energy versus time,
Shot Priscilla, C-47 station.

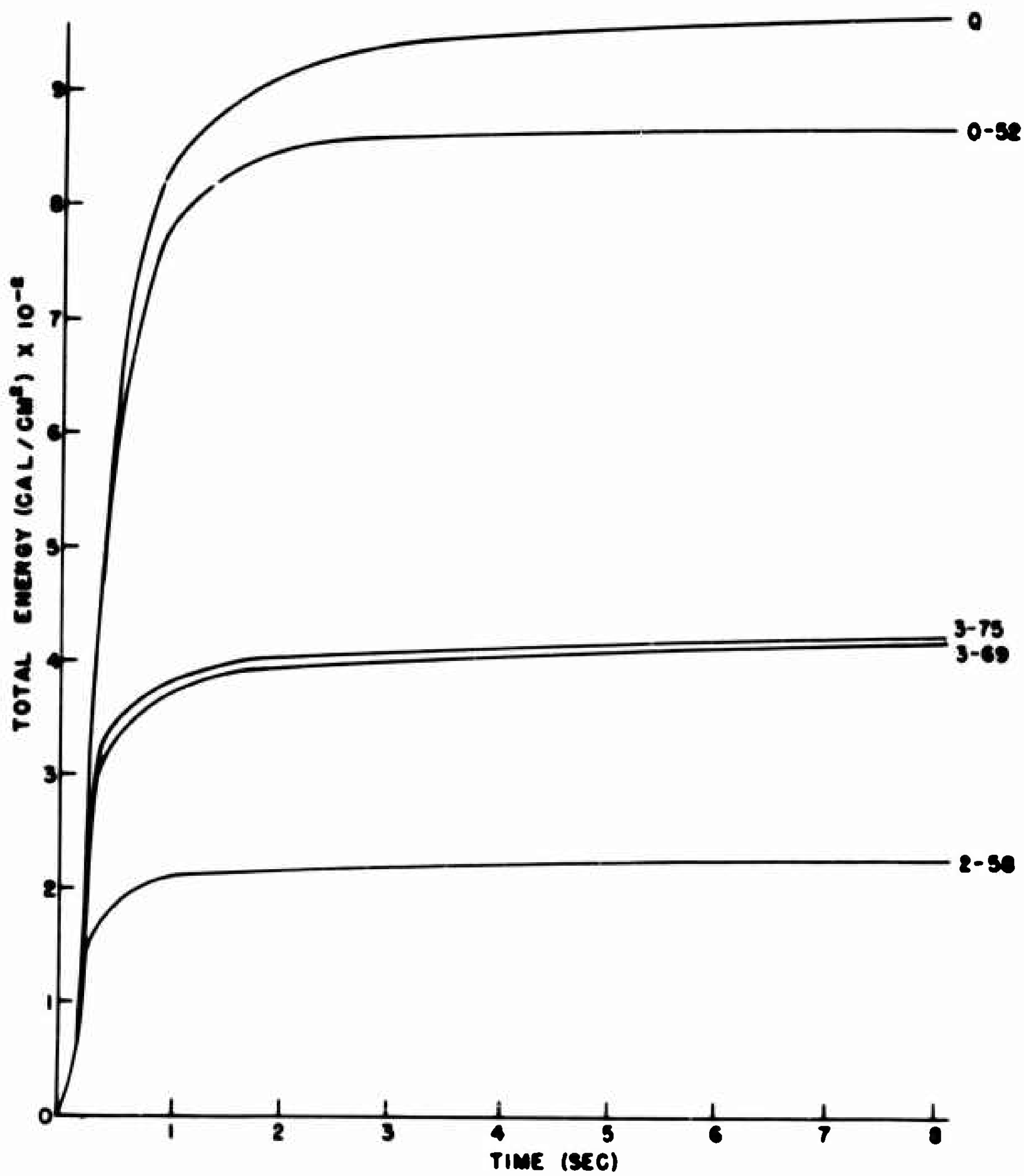

Figure 3.7 Total energy versus time, Shot Hood, C-47 station.

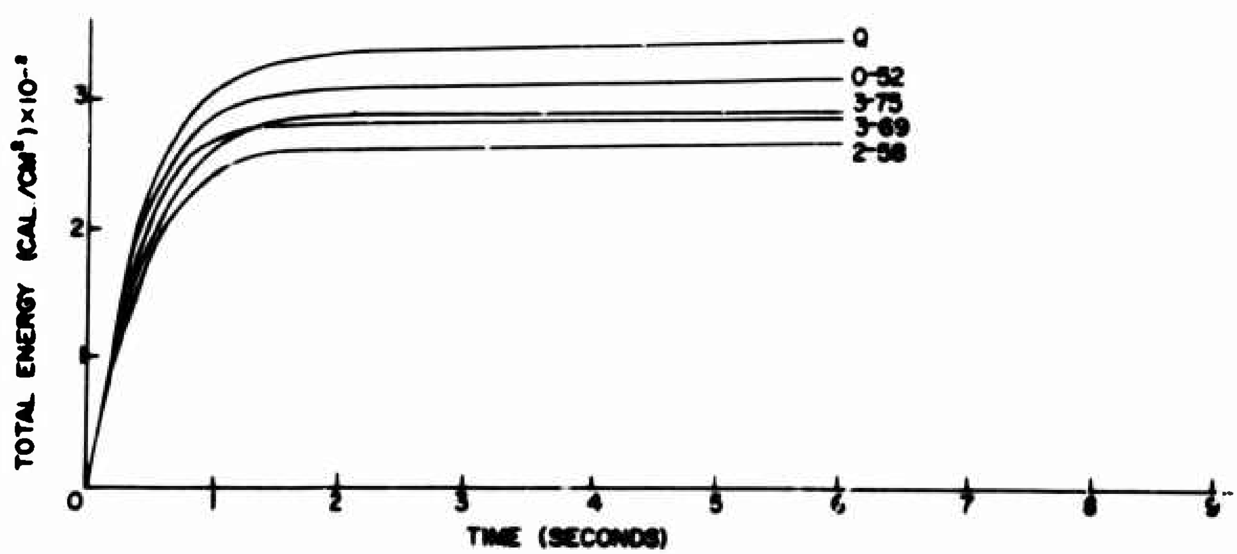

Figure 3.8 Total energy versus time, Shot Diablo, trailer station.

filter loss and indicates the broad band spectral distribution. The band pass for each filter is listed in Tables 2.2 and 2.3. These values have been corrected for filter loss by dividing the energy incident on the receiver by 0.92 for the Corning 0-52 filters and by 0.88 for the Corning 3-69, 2-58, and 3-75 filters.

Thermal energy as measured by the receiver as a function of time is listed in Tables A.1 through A.8. No corrections have been made to the data other than for heat loss of the receiver.

The broad-band spectral distribution of the thermal energy received at the site after correction for filter loss is listed in Table 3.5. Total thermal energy listed in Column 2 is the average value of the energy received by the two instruments utilizing quartz filters. The energy values listed in Columns 3 through 8 are obtained by a differencing

TABLE 3.4 THERMAL ENERGY INCIDENT AT SITE

Shot	Total Thermal Energy	
	Air	Ground
	cal/cm^2	cal/cm^2
Boltzmann	0.05	0.0552
Wilson	0.0833	0.1052
Priscilla	0.0935	0.1804
Hood	0.0963	—
Diablo	—	0.0347

method. This is accomplished by subtracting the total energy values as shown in Figures 3.1 through 3.8 to give the energy values for the indicated broad spectral bands. The measured spectral bands have been divided into three general spectral areas, namely ultraviolet from 0.22 to 0.398 micron, visible from 0.398 to 0.64 micron and infrared from 0.64 to 4.3 microns. Columns 9 through 11 indicate the percentage of the total thermal energy found in each of the three major spectral areas. It will be noted that in each of the three cases (Shots Boltzmann, Wilson and Priscilla) where both ground and air measurements were recorded, the percentage of energy in the infrared area to the total recorded energy was considerably greater for the trailer station. Likewise, the percentage of ultraviolet was significantly greater at the air station than at the ground station. The percentage of thermal energy in the visible portion of the spectrum compared to the total thermal energy remains quite constant (approximately 25 to 30 percent) for the air station and varies from 5 to 30 percent for the ground station. The sum of the percentages of these areas in each case is approximately 100 percent.

Satisfactory measurements of peak illumination were obtained and are shown graphically in Figures 3.9 through 3.13 as a percentage of peak illumination versus time. In the case of double participation, both measuring stations are shown in the same figure. Values of illumination versus time are listed in Tables A.9 through A.13 and the values of peak illumination are listed in Table 3.6.

Figure 3.14 illustrates graphically the relationship found between peak thermal irradiance and peak illumination. A straight line has been fitted and found to satisfy the equation: Peak illumination in $lumens/ft^2 = 3.8 \times 10^5$ cal/cm^2-sec $\times$ peak thermal irradiance. Inspection of Figure 3.14 indicates that this relationship can be scaled with reasonable reliability.

3.4 ANIMAL DATA

Chorioretinal burns were obtained on unprotected control animals from all shots, except for the cases of the ground station during Shot Diablo and the ground station dur-

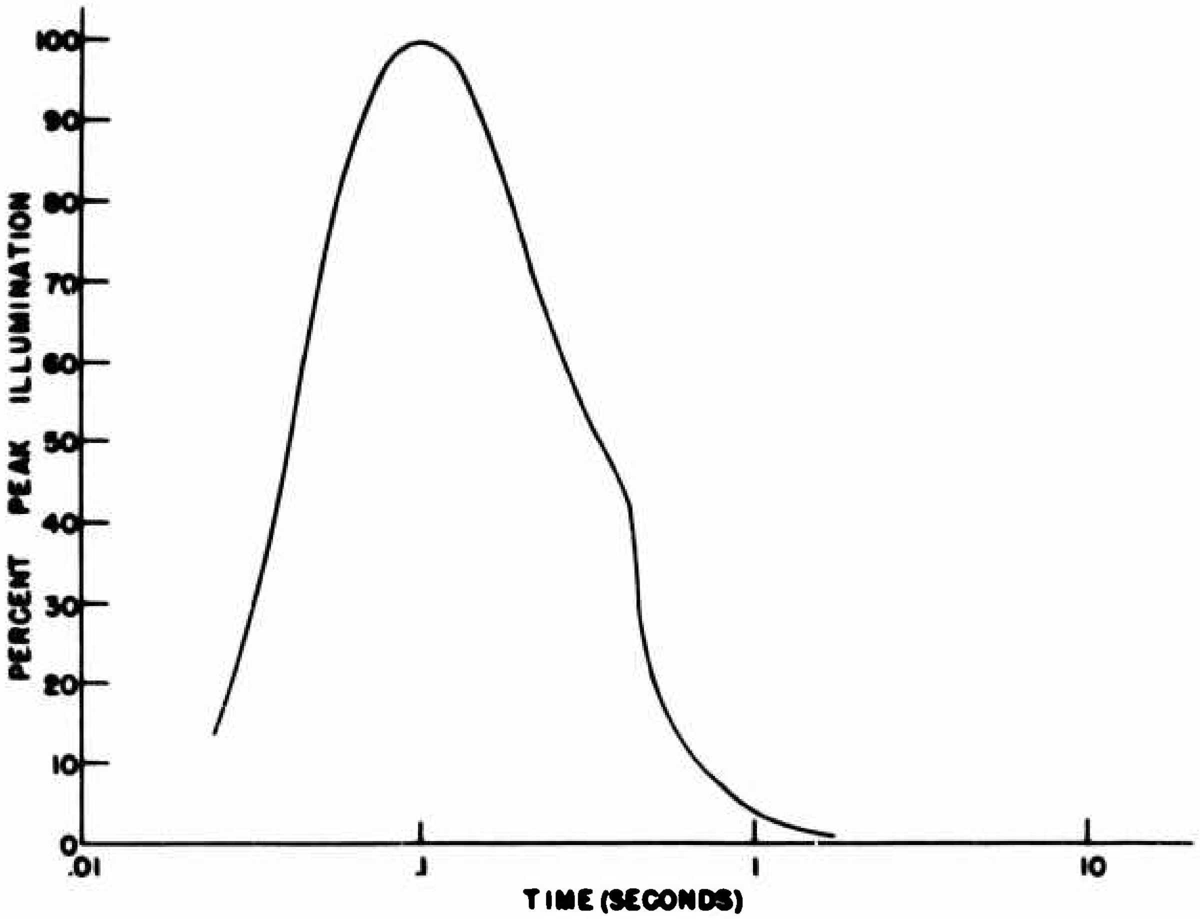

Figure 3.9 Percent peak illumination versus time, Shot Boltzmann.

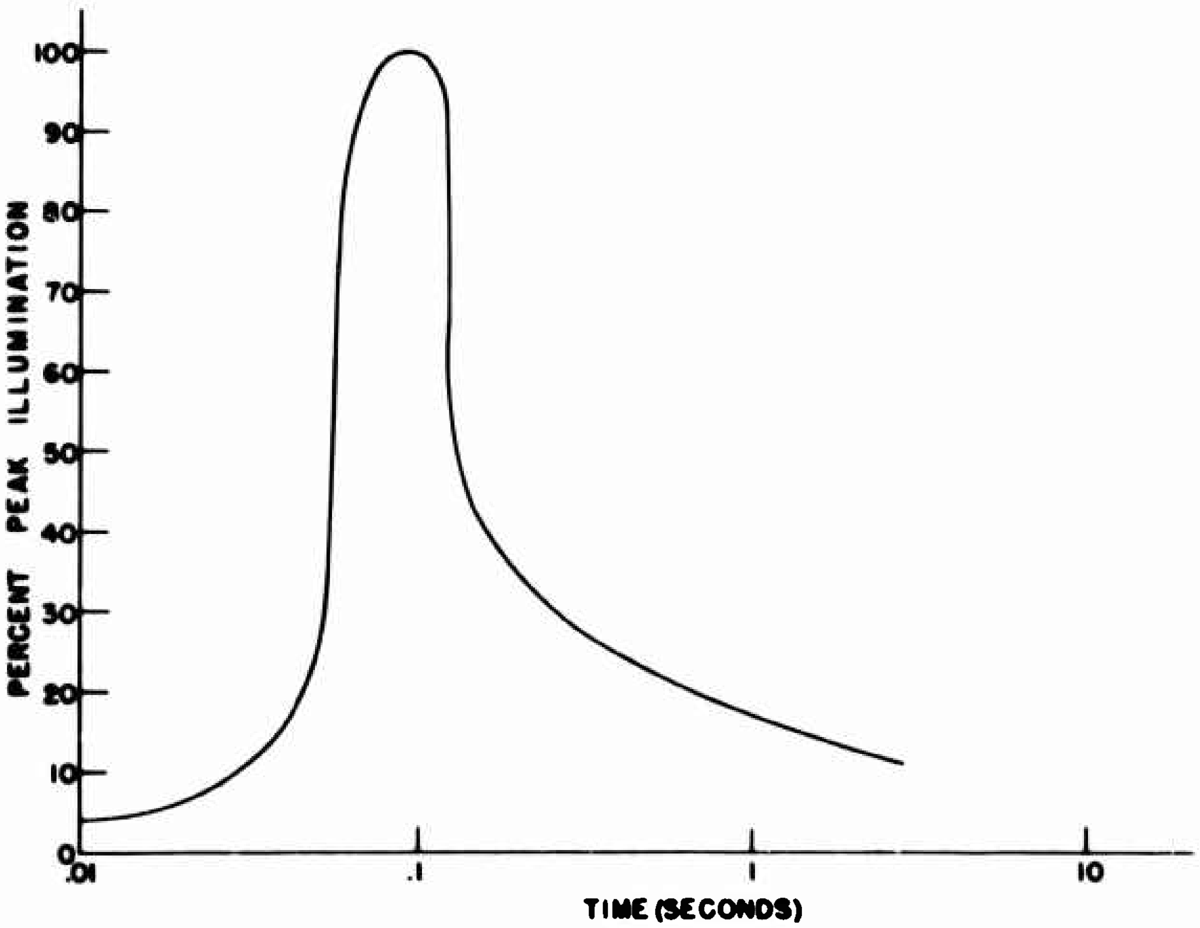

Figure 3.10 Percent peak illumination versus time, Shot Wilson.

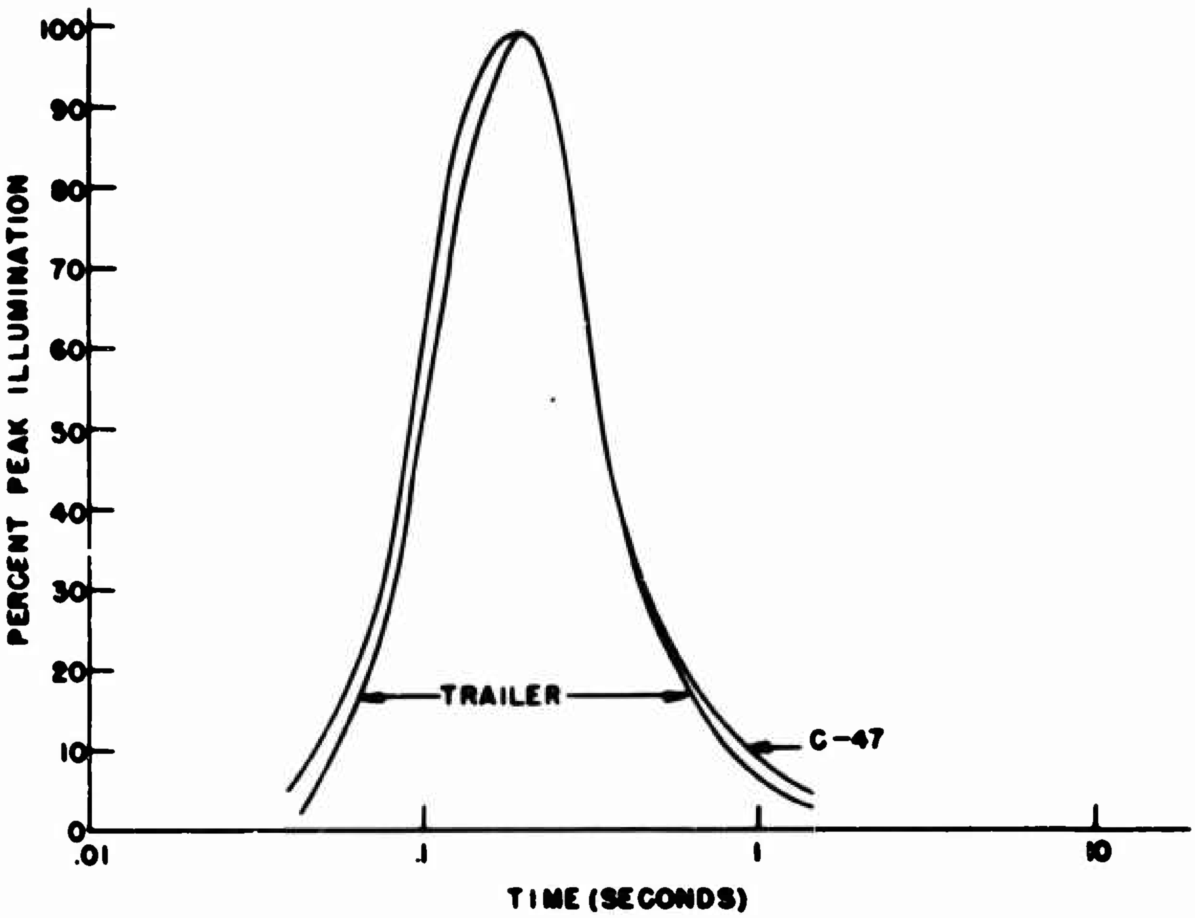

Figure 3.11 Percent peak illumination versus time, Shot Priscilla.

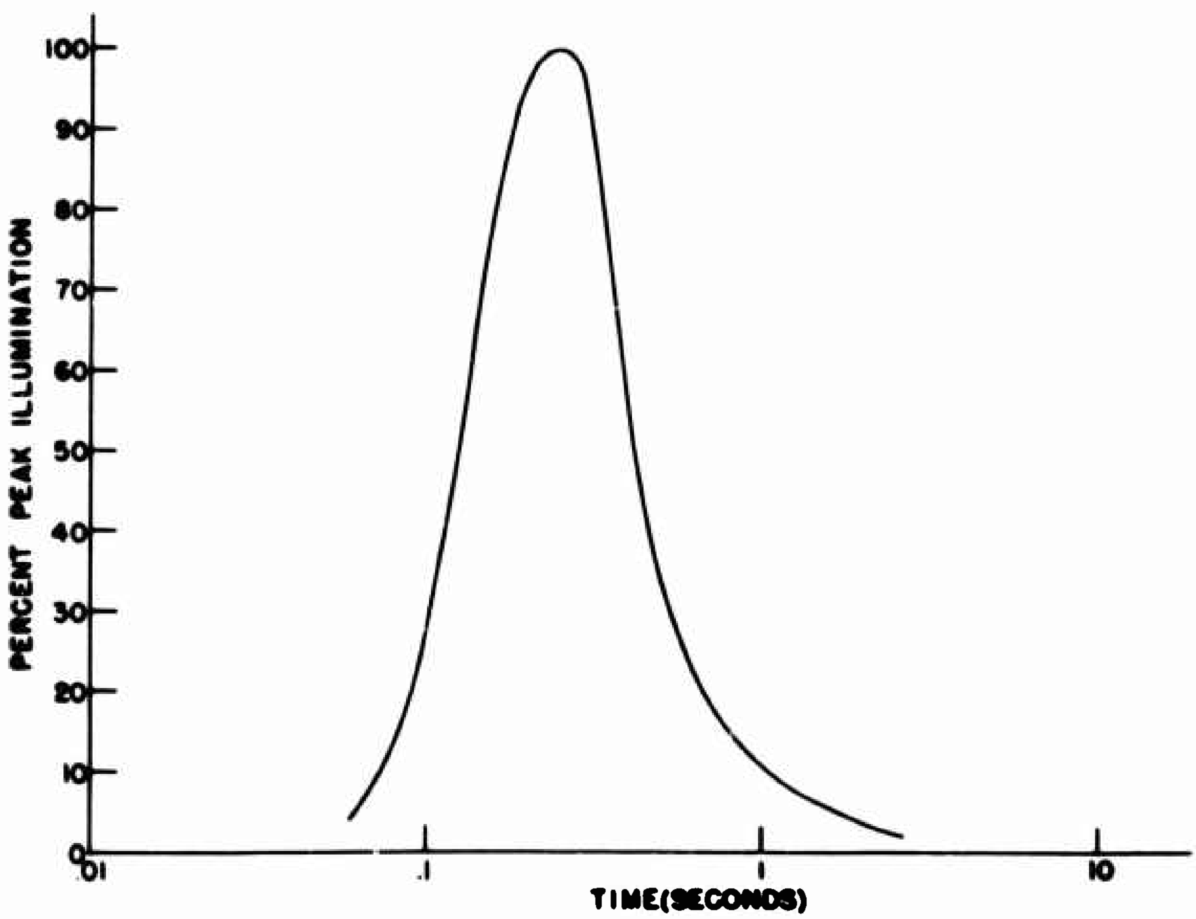

Figure 3.12 Percent peak illumination versus time, Shot Hood.

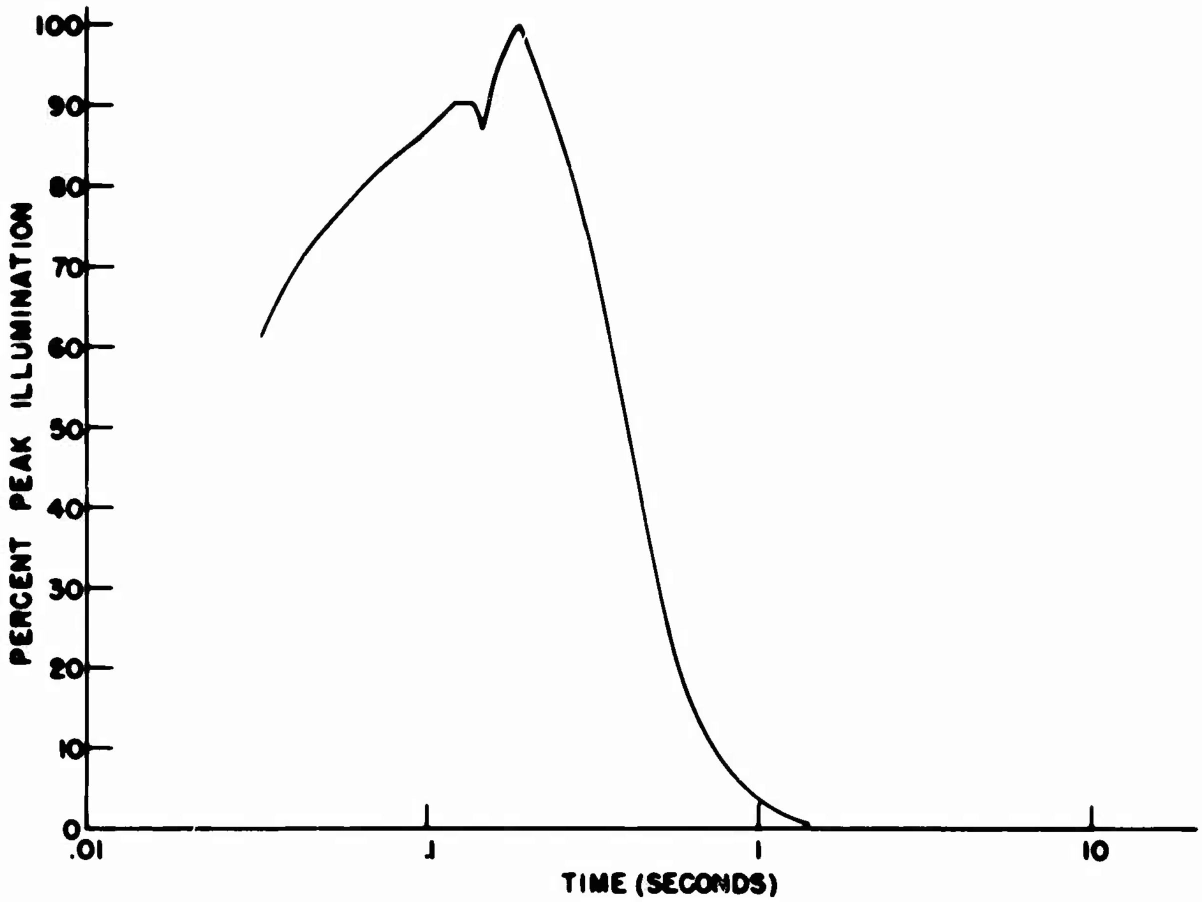

Figure 3.13 Percent peak illumination versus time. Shot Diablo.

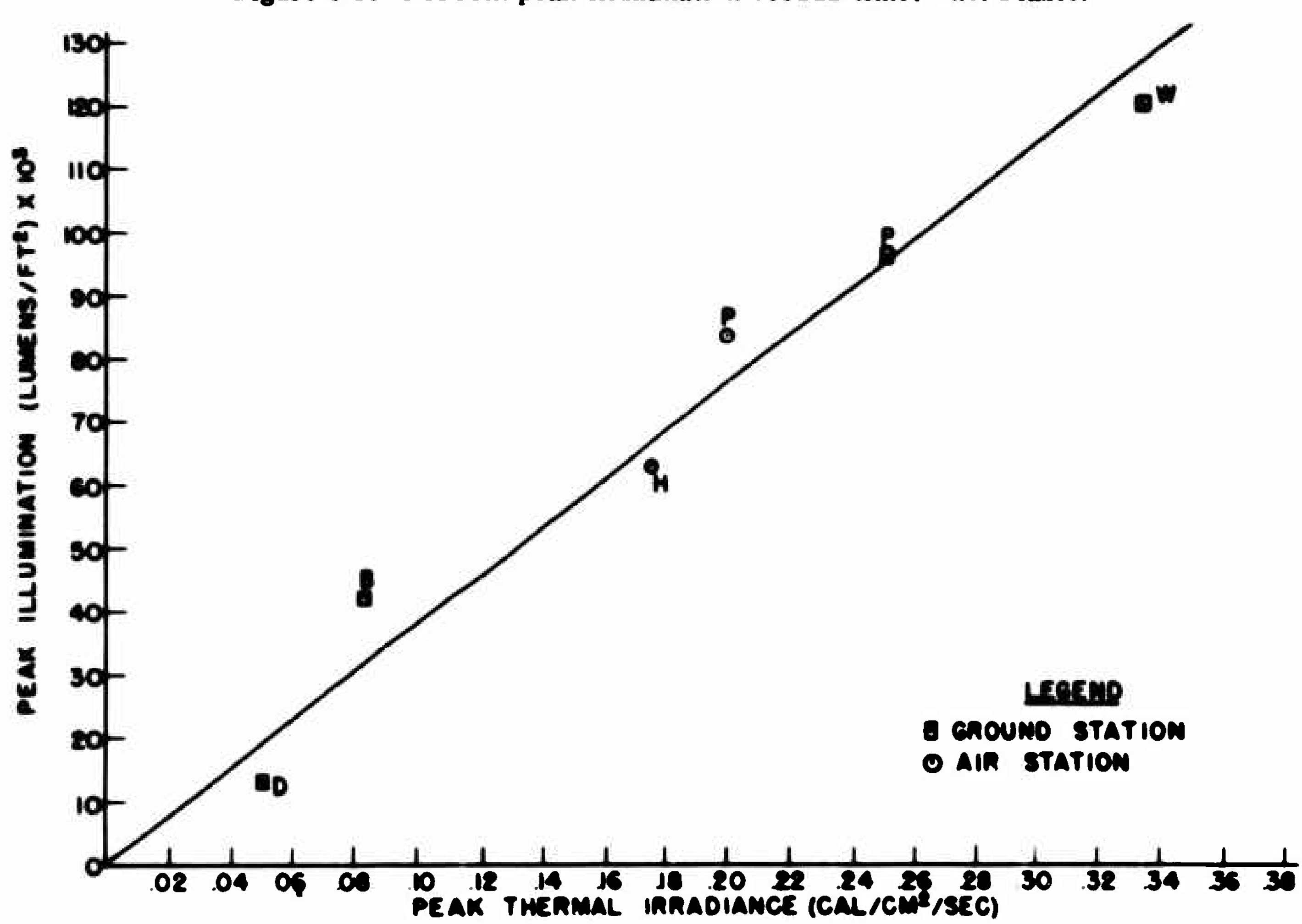

Figure 3.14 Peak thermal irrandiance versus peak illumination.

TABLE 3.5 BROAD-BAND SPECTRAL DISTRIBUTION OF THERMAL ENERGY

Location	Total Thermal Energy	Ultraviolet		Visible		Infrared		Ultraviolet	Visible	Infrared
	0.22-4.3 * cal/cm^2	0.22-0.358 * cal/cm^2	0.358-0.398 * cal/cm^2	0.398-0.527 * cal/cm^2	0.527-0.64 * cal/cm^2	0.64-2.75 * cal/cm^2	2.75-4.3 * cal/cm^2	pct	pct	pct
Boltzmann C-47	0.0500	0.0021	0.0247	†	0.0125	0.0132	†	54	25	26
Boltzmann trailer	0.0552	0.0076	†	0.0015	0.0050	0.0432	†	14	12	78
Wilson C-47	0.0833	0.0058	0.0335	0.0051	0.0169	0.0220	0.0000	47	26	26
Wilson trailer	0.1052	0.0089	0.0190	0.0128	0.0193	0.0457	0.0000	27	31	43
Priscilla C-47	0.0935	0.0030	0.0339	0.0059	0.0238	0.0269	0.0000	40	32	29
Priscilla trailer	0.1804	†	0.0453	0.0333	0.0261	0.0775	†	25	33	43
Hood C-47	0.0963	0.0086	0.0444	0.0006	0.0196	0.0231	0.0000	55	21	24
Diablo trailer	0.0347	0.0039	0.0016	0.0004	0.0014	0.0274	0.0000	16	5	79

* In microns.

† Inconclusive: indicates more energy in the longer spectral wave length band which could be attributed to trace reading error, instrumentation calibration or instrument heat loss correction techniques.

TABLE 3.6 ILLUMINANCE INCIDENT AT SITE

Shot	Distance from Ground Zero	Peak Illumination	Peak Thermal Irradiance
	yds	lumens/ft^2	(cal/cm^2)/sec
Boltzmann			
Ground	17,600	42,500	0.083
Air	21,200	Not Obtained	0.087
Wilson			
Ground	15,136	120,000	0.334
Air	19,360	Not Obtained	0.314
Priscilla			
Ground	20,649	96,000	0.25
Air	30,400	83,600	0.202
Hood			
Air	32,426	63,000	0.175
Diablo			
Ground	18,304	13,200	0.052

TABLE 3.7 ANIMAL DATA, SHOT BOLTZMANN

Control animals were exposed with no protection other than normal blink reflex.

Rabbit No.	Lesion	Remarks
Trailer site:	Total thermal energy received, 0.05 cal/cm^2	
1	◇	Control: small, minimal burn
3	◇	Control: small, minimal burn
5	–	Control: no burn detected
50	◇	Control: small, minimal burn
2	–	Inoperative shutter, no burn
51	–	Inoperative shutter, no burn
Aircraft site:	Total thermal energy received, 0.05 cal/cm^2	
10	◇	Control: small, minimal lesion
11	–	Control: no burn indicated
12	–	Inoperative shutter, no burn
13	–	Operative shutter, no burn
14	–	Operative shutter, no burn
15	–	Operative shutter, no burn

TABLE 3.8 ANIMAL DATA, SHOT WILSON

Rabbit No.	Lesion	Remarks
Trailer site: Total thermal energy received, 0.1052 cal/cm^2		
20	✓	Control: small, minimal lesion
21	–	Control: no burn detected
22	✓	Control: small, minimal lesion
Aircraft site: Total thermal energy received, 0.0833 cal/cm^2		
25	✓	Control: small, minimal lesion
26	–	Control: no burn detected

TABLE 3.9 ANIMAL DATA, SHOT PRISCILLA

Control animals exposed with no protection other than normal blink reflex.

Rabbit No.	Lesion	Remarks
Trailer site: Total thermal energy received, 0.1804 cal/cm^2		
30	–	Control: no burn detected
31	–	Control: no burn detected
32	–	Control: no burn detected
33	–	Control: no burn detected
34	–	Control: no burn detected
35	–	Control: no burn detected
36	–	Operative shutter, no burn detected
37	–	Operative shutter, no burn detected
38	–	Inoperative shutter, no burn detected
39	–	Inoperative shutter, no burn detected
Aircraft site: Total thermal energy received, 0.0935 cal/cm^2		
41	✓	Control: moderate lesion
42	✓	Control: severe lesion
43	–	Inoperative shutter, no burn detected
44	–	Inoperative shutter, no burn detected
45	–	Operative shutter, no burn detected
46	–	Operative shutter, no burn detected
47	–	Control: no burn detected

TABLE 3.10 ANIMAL DATA, SHOT HOOD

Control animals exposed with no protection other than normal blink reflex

Rabbit No.	Lesion	Remarks
Aircraft site: Total thermal energy received, 0.0963 cal/cm^2		
60	✓	Control: moderate to minimal lesion
61	✓	Control: minimal lesion
62	–	Control

TABLE 3.11 ANIMAL DATA, SHOT DIABLO

Control animals exposed with no protection other than normal blink reflex.

Rabbit No.	Lesion	Remarks
Trailer site: Total thermal energy received, 0.0347 cal/cm^2		
63	–	Control: no burn detected
64	–	Control: no burn detected
65	–	Control: no burn detected
66	–	Control: no burn detected

ing Shot Priscilla. A lower-than-expected caloric yield during Shot Diablo accounted for the lack of thermal lesions. Lack of burns from Shot Priscilla was explained by the partial obscuration of the fireball and resultant incomplete retinal image formation. In no case were animals exposed behind inoperative open shutters found to have detectable chorioretinal burns. Results for each participation are indicated in Tables 3.7 through 3.11.

Chapter 4
DISCUSSION

Participation during Operation Plumbbob was set up as the second phase of a three-phase program designed to develop eye-protective devices that would be suitable for use during nuclear operations. The protection to be afforded was twofold, i.e., flash protection and burn protection. The unprotected eye exposed to flash effects only would suffer no permanent damage, whereas the unprotected eye that was burned would be permanently damaged.

The first phase of the test program (in which rabbits were used for subjects) was carried out during Operation Redwing. This study was set up to determine burn protection only. Burn protection is not the primary concern in the development of eye protection, but it was felt that human subjects could not be used for test purposes unless complete protection from permanent injury was afforded. An electromechanical shutter closing in 500 ± 50 μsec proved to be adequate protection from a permanent burn.

The second phase of the study, wherein human subjects would be exposed to the radiant effects of a nuclear detonation, therefore became possible. During this phase the subjects were to be positioned at a precalculated distance such that maximum illumination would be obtained without exceeding the retinal burn threshold in case of shutter failure.

The third phase of this study was an operational suitability test (service test). This phase would start when sufficient prototypes (approximately 10 each) had been delivered to Wright Air Development Center (WADC). Delivery was anticipated during the first quarter of fiscal year 1959.

Project 4.2 participation in Operation Plumbbob shots and shot objectives was as follows:

1. Shot Boltzmann. To confirm predicted thermal yield and check equipment by obtaining thermal and photometric data at a ground and at an air station.
2. Shot Wilson. To expose human subjects using electromechanical shutters and determine the time sequence for recovery of visual effectiveness.
3. Shot Priscilla. To test shutters in an inoperative condition (with animal subjects) to determine the feasibility of exposing human subjects under similar conditions at a distance from ground zero that would yield significant radiant energy to cause flash effects.
4. Shot Hood. To expose human subjects using inoperative open shutters to determine the flash effects objectively (for comparative purposes) with no protection other than the inherent 80 percent absorption of the open shutter.
5. Shot Diablo. To expose human subjects through shutters that close in approximately 1 msec in order to investigate the possibility that the electromechanical shutters might be overdesigned. In addition, to test a light-restrictive filter (narrow-band transmittance) designed by the Navy, for effectiveness in minimizing flash-recovery time.

4.1 SHOT BOLTZMANN

One of the two control (no-protection) animals exposed in the air station received a minimal burn, and three of the four controls at the ground station received minimal

burns. None of the eight protected animals showed a burn or any edema when examined ophthalmoscopically and photographed approximately 2 hours after exposure.

Data gathered by the thermal-measuring instrumentation confirmed the prediction of total thermal energy that would be received at the station on the ground and in the air.

As a result of this confirmation, the exposure of human subjects for a period of 500 μsec was possible, and plans for such an exposure were initiated.

4.2 SHOT WILSON

Subject exposure during Shot Wilson was carried out as planned. The recovery of useful vision, as determined by the ability of the subjects to read aircraft instruments, was timed by an examiner. The mesopic acuity was determined by the ability of the subjects to read a nyctometer chart after certain periods of time.

The subjects at both the air and ground stations were able to accomplish their particular tasks immediately after exposure, thus proving the effectiveness of the closure time incorporated into the shutters. All the shutters operated, and closure times were recorded at 550 ± 50 μsec.

The control exposures (rabbits with no protection) showed a burn incidence of over 50 percent. This indicated the effectiveness of the shutter in preventing burns.

4.3 SHOT PRISCILLA

Rabbits were exposed to the radiant energy of this shot, through inoperative open shutters, at a distance from ground zero that would yield sufficient illumination to cause a loss of retinal sensitivity for a measurable length of time. Animals were exposed so that the amount of energy received would closely approximate the human chorioretinal burn threshold. The rabbit burn threshold was lower than the human burn threshold, due to the slower blink reflex (300 msec average for rabbits, 100 msec average for humans) and the location of the nodal point. The rabbit's nodal point is closer to the retina, thus causing the energy received to be concentrated over a smaller retinal area than in the human eye.

The exposures were accomplished, and no burns were received through the inoperative shutters. The energy received at the air station was greater than anticipated, but the inherent absorption of the shutter being tested (approximately 80 percent) was sufficient to prevent permanent retinal damage. The control animals at the air station received chorioretinal burns, thus indicating that sufficient energy was present to cause permanent chorioretinal damage to the unprotected rabbit eye. (Total thermal energy received at each site is indicated in the shot table.) No chorioretinal burns were received at the ground station. Although the total energy received would be expected to produce chorioretinal lesions, none were detected on postshot examination. The explanation is undoubtedly based on lack of complete line of sight and, therefore, incomplete retinal image formation. With the confirmation of pretest predictions, the next step in the test of the shutters was in order.

4.4 SHOT HOOD

During this shot, human subjects were exposed through operational and nonoperational (open) shutters to obtain objective measurements that could be used comparatively to determine the extent of protection afforded by shutter closure and that afforded by the inherent density of the shutters. The results of this test were conclusive, in that the

exposure through nonoperational shutters resulted in a minimum recovery of 10 seconds to aircraft instrument recognition and up to 90 seconds for return of mesopic vision. The recovery time needed to read instruments did point up the possibility that the shutters were overdesigned, i. e., the closure was faster than necessary to prevent loss of visual effectiveness. This part was of vital concern, due to the energy requirements of the shutter power supply. If the closure time could be cut in half, the power requirements could be cut in half. Consequently, participation in the final shot was devoted to exploring the possibility of a slower shutter-closure time.

4.5 SHOT DIABLO

Shot Diablo participation was designed to investigate several remaining problems. In addition to the slowed-down shutter exposure, an exposure was set up for a light-restricting filter designed by the Navy and manufactured by Baird Associates of Cambridge, Massachusetts.

An exposure through a nonoperational (open) shutter andoone of a naked human eye, with a translucent plate of glass used as a secondary light source, was also accomplished. This was designed to test the recovery of an eye when a nuclear weapon is detonated in such a manner that the eye receives radiation only through a cloud. The results of this test showed that an eye exposed in this manner was more acutely affected than the eye exposed to direct energy. The recovery time to partial vision (viewing around or through the after-image) was shorter when the light source was viewed directly, but the possibility of permanent damage was great. However, when the light source was viewed through a secondary source, the possibility of permanent damage was almost nonexistent due to the lack of image formation; but the glare effect was all-encompassing, and the individual was completely flash blinded for a period of time. The time may or may not be critical, depending on the visual task at hand.

The narrow-band-transmittance filter appeared to be effective in minimizing recovery after exposure and preventing chorioretinal burns. However, more will have to be known about the filter before firm recommendations can be made.

Chapter 5
CONCLUSIONS

Electromechanical shutters tested in the field during Operation Plumbbob provided flash and burn protection of the exposed human and animal eyes at the distances and yields indicated in Table 2.1. As a result of these tests as well as past field studies of chorioretinal burns referenced in the context of this report, a closure time of 500 μsec from onset of flash will furnish adequate protection against the deleterious effects of visible and thermal radiant energy incident from low-altitude and low-yield nuclear detonations.

Chapter 6
RECOMMENDATIONS

1. A mechanical shutter utilizing the closure method reported should be manufactured as a limited standard goggle and be service tested for operational suitability.

2. Any further studies should include laboratory work, with the use of illumination data gathered during the Plumbbob series, on recovery time to needed visual acuity in order to perform a given task at a given distance from a nuclear detonation. The pertinent tasks and distances for these studies would be determined by Tactical Air Command, Air Defense Command, and Strategic Air Command to correlate with tactics currently employed, or contemplated, by them.

3. Utilizing the information in Item 2 above, a study could be made of the effectiveness of various methods of flash protection now available. Particular attention should be given to slower closure speeds in electromechanical shutters and to fixed-density goggles and interference filters.

4. As an end item, the studies recommended in Items 2 and 3 above would permit the publication of a manual of eye protection from high-intensity light sources that would permit the prediction of the extent of protection needed to perform a given task and what protective method or methods would best furnish such protection.

5. A more sophisticated measurement of illumination, spectral distribution and total thermal energy would be desirable to augment the results of this test. These measurements should be accomplished over narrower spectral beamed widths and with a much shorter time resolution.

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Appendix
MEASUREMENT of THERMAL and PHOTOMETRIC ENERGY at SITE

Tables A.1 through A.8 are the tabulated thermal energy measurements as a function of time incident on the receiver and are not adjusted for filter loss. This information is listed here because it is beyond the scope of this report to perform detailed scaling or diagnostic weapon capabilities studies.

Tables A.9 through A.13 are the tabulated photometric measurements as a function of time. These values are represented graphically in Figures 3.9 through 3.13 and are included here for reference purposes.

Figures A.1 through A.7 are the GSAP camera first frame photographs used to establish the orientation of the thermal and photometric instrumentation. These GSAP cameras operated at 64 frame/second and the lenses had a focal light of 35 mm.

Figure A.1 Gun-sight-aiming-point photograph, Shot Boltzmann, trailer. Frame No. 1.

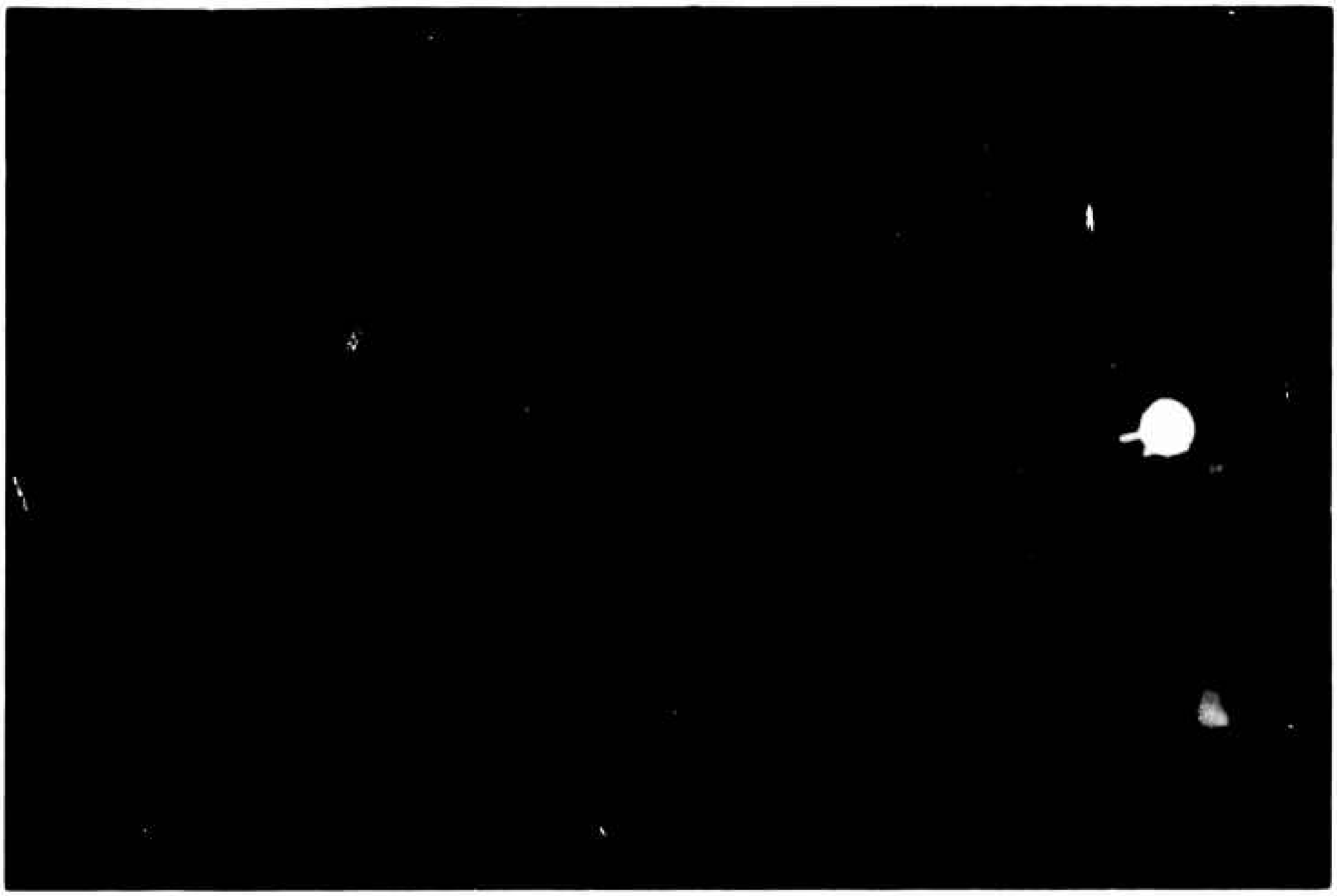

Figure A.2 Gun-sight-aiming-point photograph, Shot Wilson, C-47. Frame No. 1.

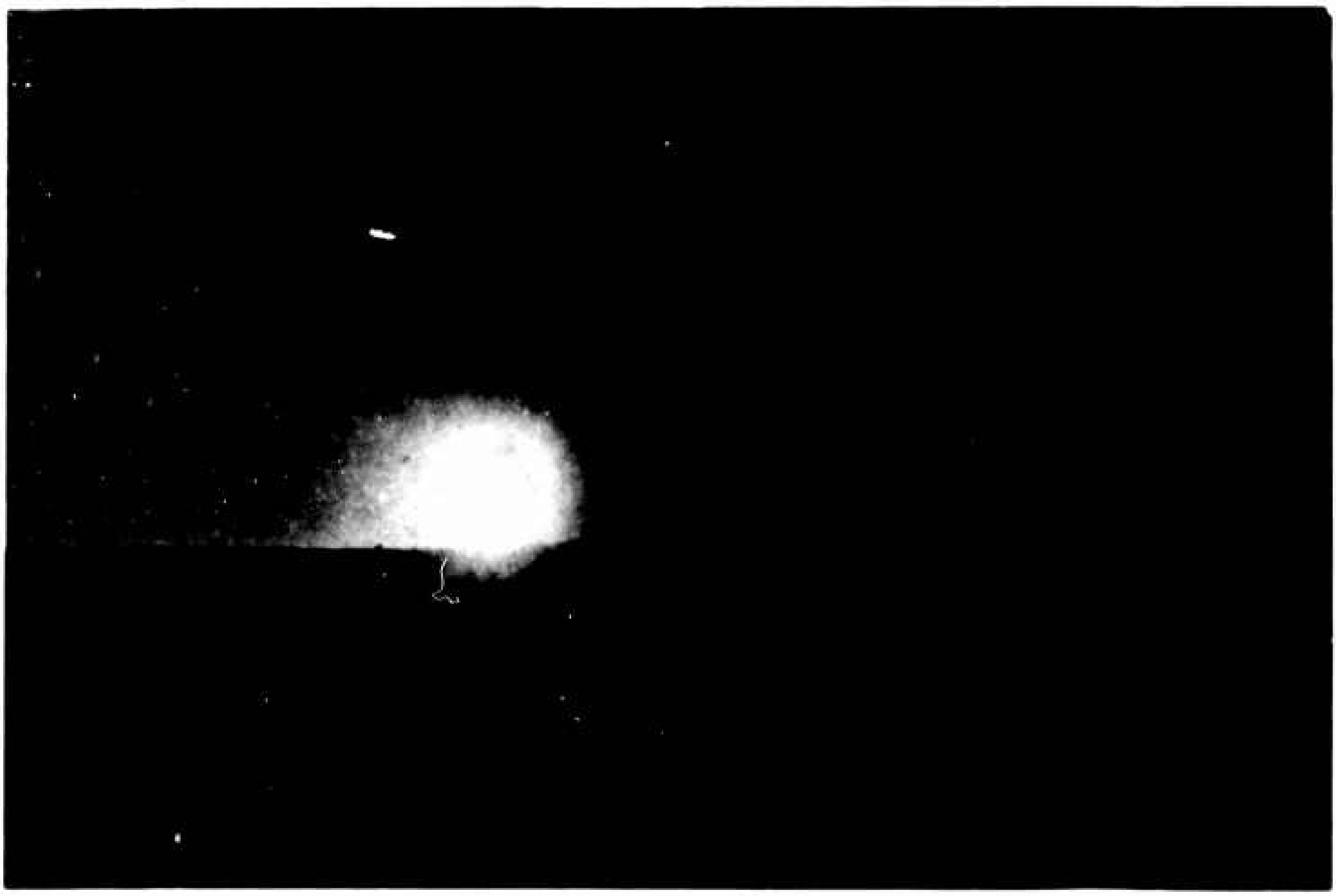

Figure A.3 Gun-sight-aiming-point photograph, Shot Wilson, trailer. Frame No. 1.

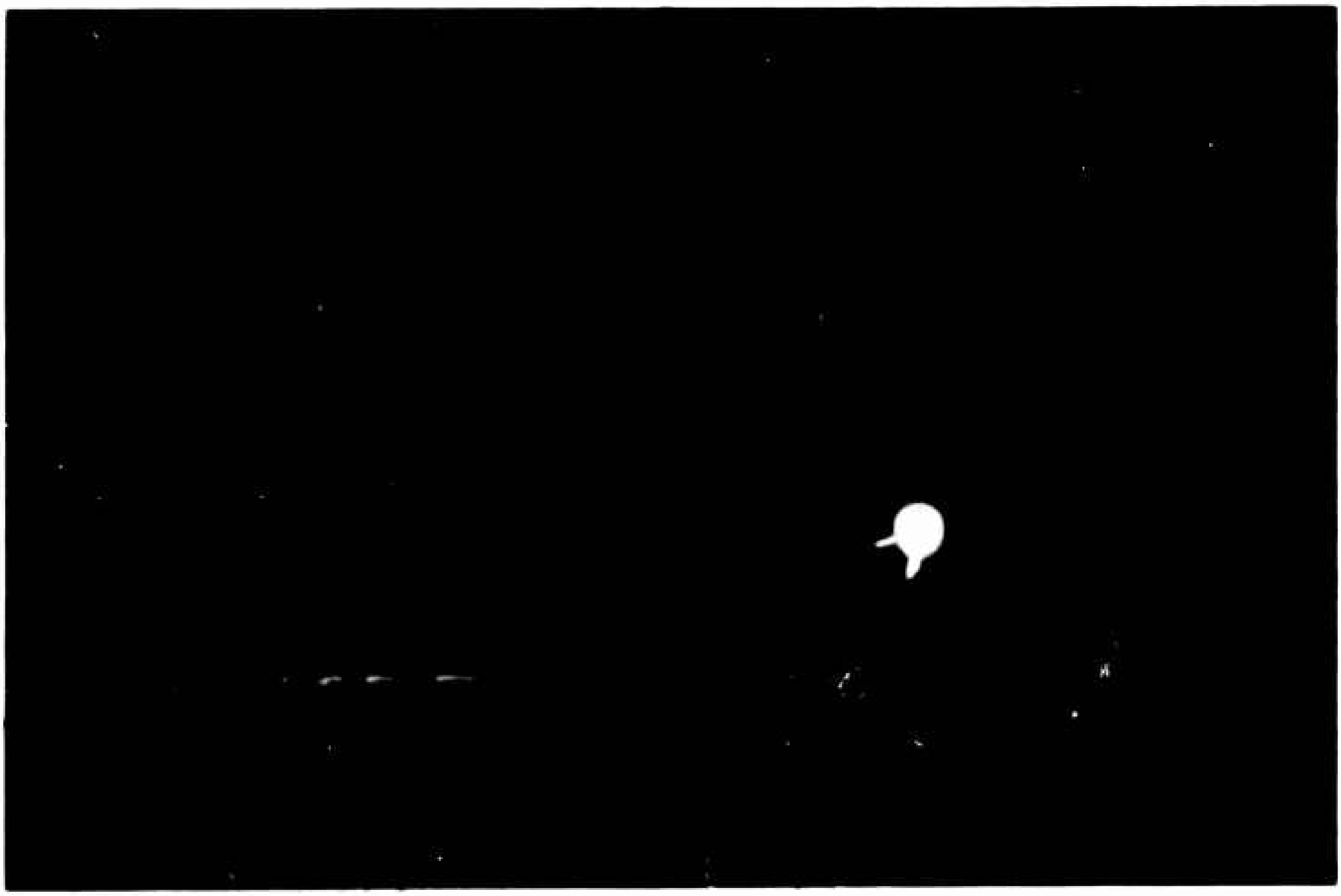

Figure A.4 Gun sight-aiming-point photograph, Shot Priscilla, C-47. Frame No. 1.

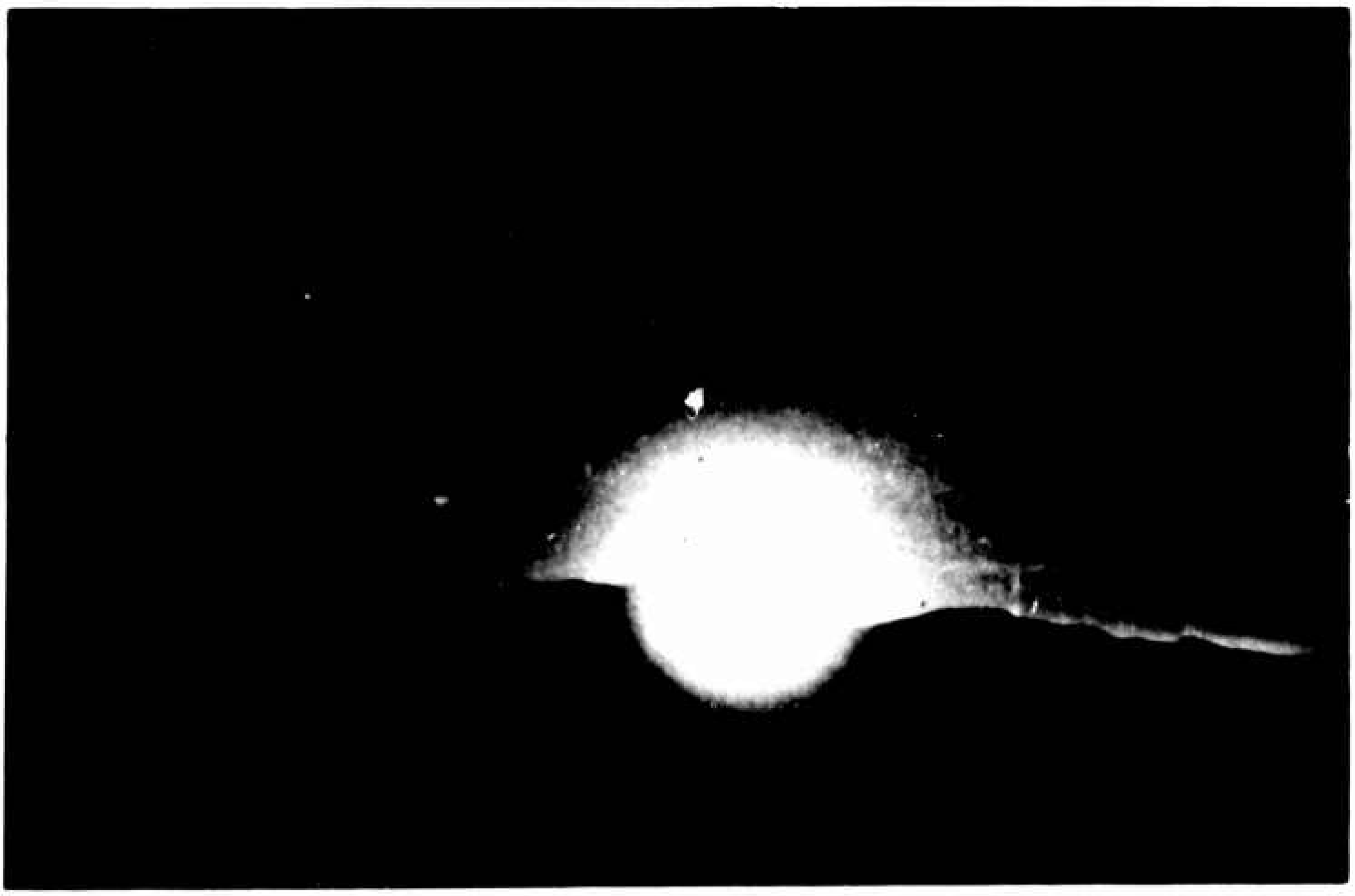

Figure A.5 Gun-sight-aiming-point photograph, Shot Priscilla, trailer. Frame No. 1.

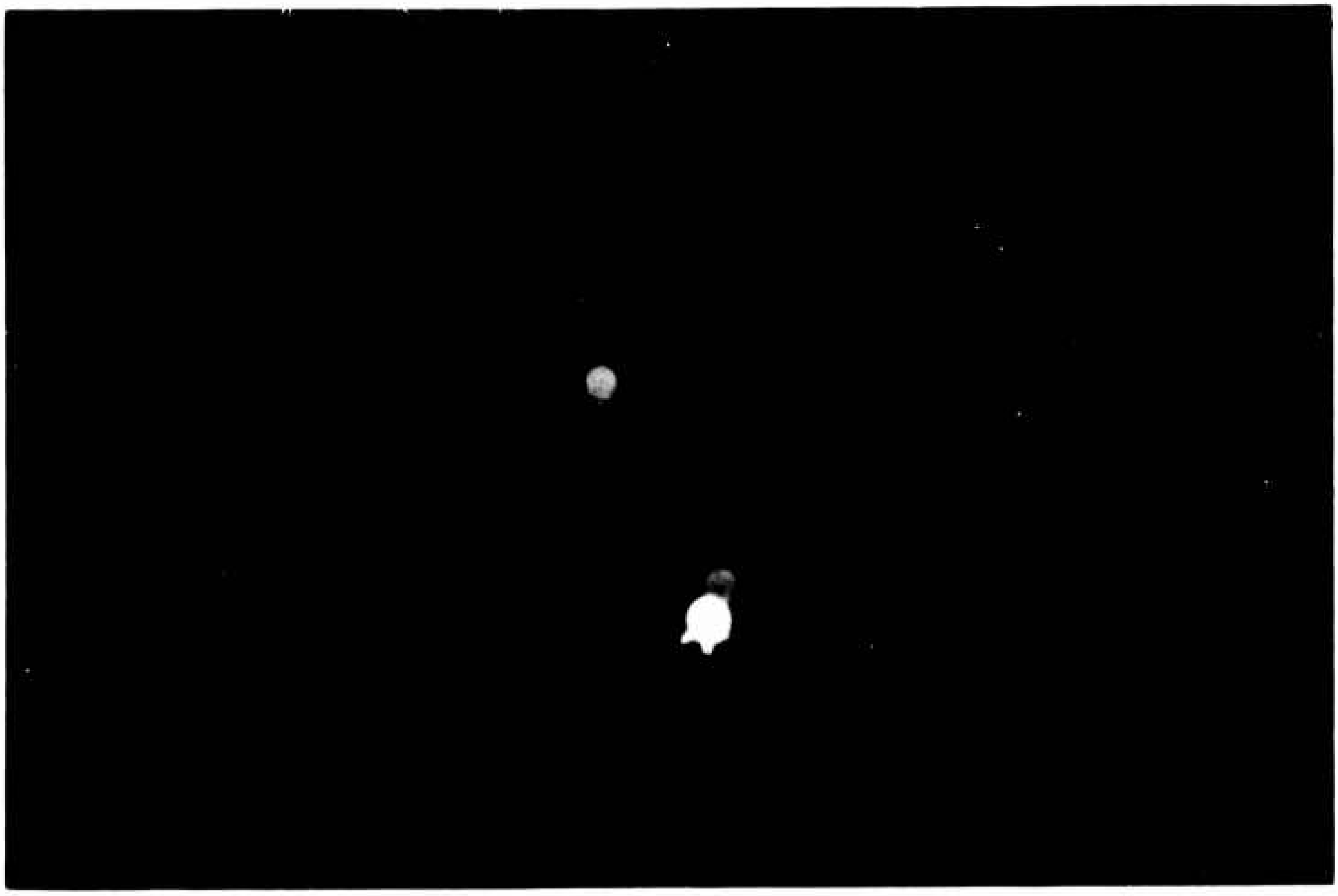

Figure A.6 Gun-sight-aiming-point photograph, Shot Hood, C-47. Frame No. 1.

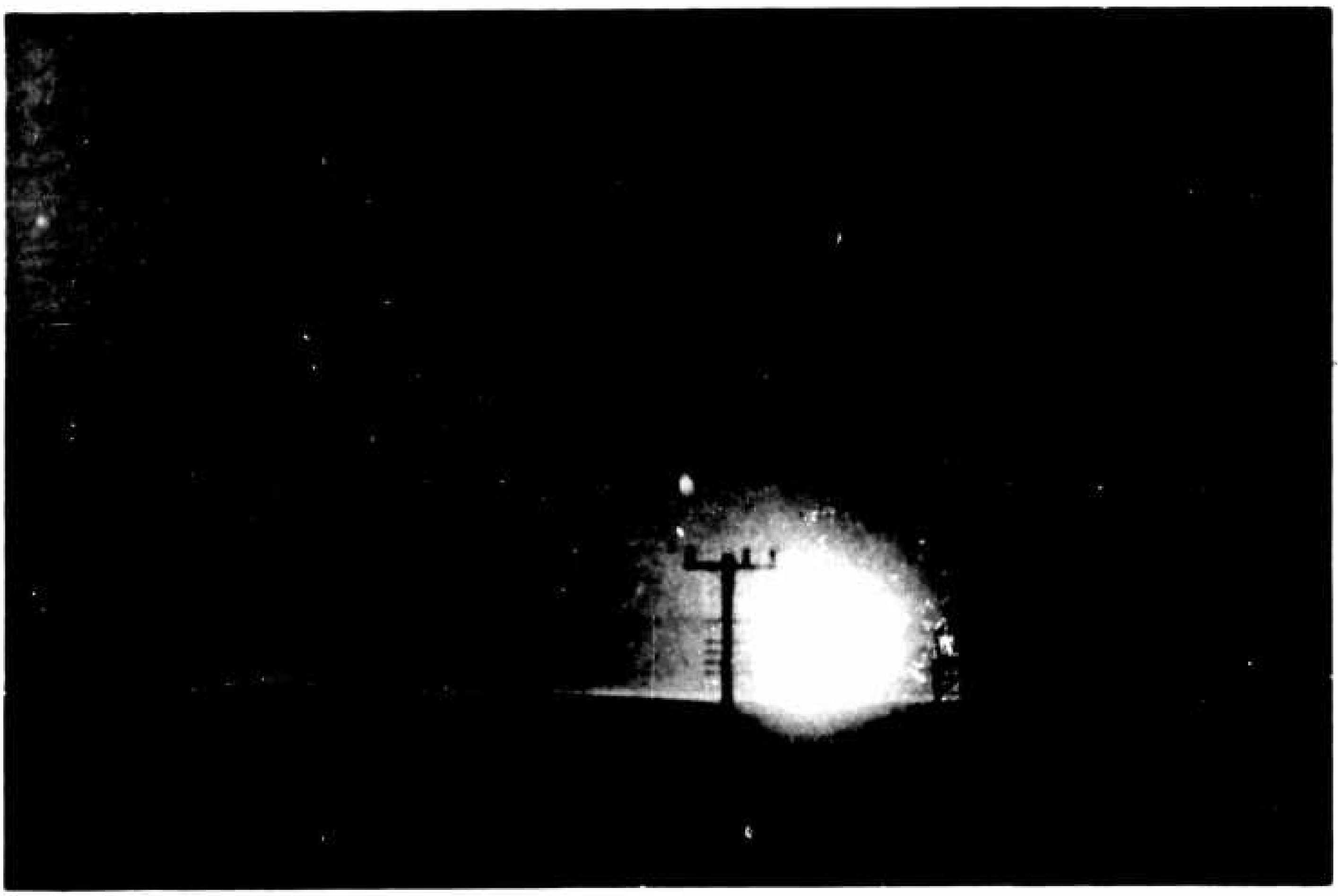

Figure A.7 Gun-sight-aiming-point photograph, Shot Diablo, trailer. Frame No. 1.

TABLE A.1 THERMAL ENERGY TO RECEIVER AS FUNCTION OF TIME, SHOT BOLTZMANN, C-47 STATION

Time	XX-7 Q	XX-13 Q	XX-12 Q	MH-9 3-69	MH-7 2-58	MH-5 3-75
sec	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2
0.07	0.36×10^{-2}	0.35×10^{-2}	0.38×10^{-2}	0.20×10^{-2}	0.14×10^{-2}	0.20×10^{-2}
0.12	0.77	0.70	0.82	0.46	0.31	0.48
0.14	0.97	0.88	1.01	0.60	0.38	0.60
0.18	1.30	1.37	1.37	0.81	0.50	0.84
0.23	1.69	1.83	1.74	1.34	0.62	1.06
0.34	2.44	2.52	2.44	1.42	0.81	1.42
0.52	3.32	3.31	3.20	1.81	1.00	1.78
0.78	3.86	3.83	3.75	2.10	1.12	1.99
1.30	4.21	4.13	4.02	2.13	1.13	2.04
2.08	4.46	4.31	4.18	2.20	1.14	2.04
3.90	4.61	4.46	4.30	2.24	1.16	2.04
6.00	4.60	4.61	4.41	2.26	1.16	2.04

TABLE A.2 THERMAL ENERGY TO RECEIVER AS FUNCTION OF TIME, SHOT WILSON, C-47 STATION

Time	XX-7 Q	XX-13 Q	XX-12 Q	MH-9 3-69	MH-7 2-58	MH-5 3-75
sec	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2
0.05	0.32×10^{-2}	0.32×10^{-2}	0.38×10^{-2}	0.27×10^{-2}	0.17×10^{-2}	0.27×10^{-2}
0.09	1.36	1.50	1.39	0.88	0.53	0.99
0.11	2.04	2.20	1.98	1.24	0.71	1.42
0.14	2.88	3.18	2.82	1.66	0.94	1.89
0.18	3.74	4.03	3.64	2.08	1.16	2.38
0.26	4.78	5.13	4.68	2.55	1.39	2.92
0.40	5.74	5.99	5.49	2.92	1.55	3.36
0.60	6.40	6.57	6.09	3.08	1.59	3.57
0.99	6.76	6.72	6.31	3.11	1.60	3.60
1.59	7.05	6.96	6.59	3.18	1.71	3.68
2.97	7.48	7.43	6.86	3.36	1.87	3.83
5.00	7.65	7.67	7.04	3.42	1.94	3.87

TABLE A.3 THERMAL ENERGY TO RECEIVER AS FUNCTION OF TIME, SHOT PRISCILLA, C-47 STATION

Time	XX-7 Q	XX-13 Q	XX-12 0-52	MH-9 3-69	MH-7 2-58	MH-5 3-75
sec	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2
0.09	0.54×10^{-2}	0.54×10^{-2}	0.47×10^{-2}	0.36×10^{-2}	0.24×10^{-2}	0.32×10^{-2}
0.17	1.86	2.00	1.84	1.22	0.76	1.24
0.20	2.48	2.79	2.51	1.63	0.95	1.66
0.26	3.83	4.07	3.77	2.27	1.28	2.40
0.33	4.90	5.22	4.96	2.86	1.57	3.08
0.48	6.45	6.64	6.28	3.44	1.83	3.77
0.75	7.59	7.62	7.31	3.82	2.01	4.32
1.10	7.98	8.10	7.83	3.96	2.04	4.53
1.83	8.18	8.27	8.06	4.06	2.12	4.64
2.93	8.32	8.48	8.16	4.25	2.25	4.80
5.49	8.50	8.75	8.33	4.46	2.37	4.98

TABLE A.4 THERMAL ENERGY TO RECEIVER AS FUNCTION OF TIME, SHOT HOOD, C-47 STATION

Time	XX-7 Q	XX-13 Q	XX-12 0-52	MH-9 3-69	MH-7 2-58	MH-5 3-75
sec	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2
0.13	0.75×10^{-2}	0.72×10^{-2}	0.55×10^{-2}	0.41×10^{-2}	0.30×10^{-2}	0.37×10^{-2}
0.23	2.14	2.19	1.97	1.32	0.84	1.28
0.29	3.27	3.20	3.12	1.89	1.14	1.85
0.36	4.43	4.27	4.22	2.44	1.43	2.46
0.47	5.68	5.55	5.38	2.92	1.68	2.94
0.68	6.99	6.86	6.59	3.25	1.81	3.28
1.04	8.01	7.82	7.44	3.42	1.86	3.43
1.56	8.64	8.31	7.85	3.45	1.87	3.48
2.60	8.84	8.41	7.92	3.46	1.90	3.53
4.16	9.01	8.61	7.96	3.57	1.95	3.61
7.80	9.09	8.81	7.97	3.72	2.02	3.75
10.00	9.13	8.88	8.07	3.76	2.03	3.81

TABLE A.5 THERMAL ENERGY TO RECEIVER AS FUNCTION OF TIME, SHOT BOLTZMANN, TRAILER STATION

Time	XX-27 Q	XX-32 Q	XX-25 0-52	XX-29 3-69	XX-24 2-58	XX-26 3-75
sec	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2
0.07	0.34×10^{-2}	0.36×10^{-2}	0.23×10^{-2}	0.36×10^{-2}	0.31×10^{-2}	0.18×10^{-2}
0.12	0.69	0.73	0.64	0.73	0.58	0.51
0.14	0.84	0.89	0.81	0.87	0.69	0.65
0.18	1.19	1.21	1.11	1.16	0.85	0.93
0.23	1.59	1.59	1.47	1.49	1.13	1.26
0.34	2.43	2.38	2.21	2.13	1.64	1.98
0.52	3.42	3.26	3.14	2.84	2.43	2.95
0.78	4.08	3.87	3.66	3.31	2.94	3.65
1.30	4.61	4.38	[illegible]	3.63	3.26	4.07
2.08	4.87	4.61		3.84	3.44	4.31
3.90	5.03	4.79	4.31	4.13	3.66	4.32
6.00	5.06	4.98	4.34	4.23	3.76	4.33
8.00	5.09	5.07	4.38	4.24	3.80	4.37

TABLE A.6 THERMAL ENERGY TO RECEIVER AS FUNCTION OF TIME, SHOT WILSON, TRAILER STATION

Time	XX-27 Q	XX-32 Q	XX-25 0-52	XX-29 3-69	XX-24 2-58	XX-26 3-75
sec	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2
0.05	0.05×10^{-2}	0.05×10^{-2}	0.05×10^{-2}	0.04×10^{-2}	0.05×10^{-2}	0.05×10^{-2}
0.07	0.29	0.35	0.27	0.26	0.14	0.30
0.11	1.25	1.22	1.05	0.73	0.43	0.86
0.15	2.72	2.60	2.45	1.73	1.20	2.12
0.18	3.42	3.20	2.98	2.18	1.63	2.91
0.23	4.08	3.85	3.60	2.65	1.94	3.51
0.34	5.00	4.23	4.38	3.23	2.39	4.28
0.52	5.90	5.57	5.14	3.71	2.72	4.93
0.78	6.64	6.40	5.73	4.04	2.92	5.28
1.30	7.47	7.42	6.49	4.46	3.17	5.64
2.00	8.33	7.88	7.33	4.91	3.51	6.08
2.40	8.74	8.90	7.70	5.12	3.67	6.27
3.50	9.54	9.24	8.42	5.52	3.88	6.64
4.50	9.87	9.35	8.75	5.67	3.95	6.78
6.00	10.02	9.35	8.86	5.68	3.98	6.80

TABLE A.7 THERMAL ENERGY TO RECEIVER AS FUNCTION OF TIME, SHOT PRISCILLA, TRAILER STATION

Time	XX-27 Q	XX-32 Q	XX-25 0-52	XX-29 3-69	XX-24 2-58	XX-26 3-75
sec	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2
0.09	0.44×10^{-2}	0.41×10^{-2}	0.45×10^{-2}	0.35×10^{-2}	0.30×10^{-2}	0.35×10^{-2}
0.17	1.75	1.59	1.58	1.24	0.85	1.34
0.20	2.58	2.32	2.43	1.78	1.25	2.05
0.26	3.93	3.69	3.88	2.77	1.95	3.23
0.33	5.32	5.07	5.38	3.69	2.77	4.48
0.48	7.50	7.16	7.36	5.06	4.00	6.57
0.73	9.48	8.93	9.17	6.43	4.91	8.53
1.10	10.85	10.54	10.49	7.08	5.53	9.40
1.83	12.18	12.24	11.97	7.58	5.89	10.24
2.93	13.58	13.95	13.40	7.95	6.02	10.83
5.50	15.46	16.55	15.95	8.61	6.73	11.82
7.00	15.79	17.16	16.54	9.00	6.78	12.07
9.00	15.82	17.37	16.76	9.12	6.82	12.05

TABLE A.8 THERMAL ENERGY TO RECEIVER AS FUNCTION OF TIME, SHOT DIABLO, TRAILER STATION

Time	XX-27 Q	XX-32 Q	XX-25 0-52	XX-29 3-69	XX-24 2-58	XX-26 3-75
sec	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2	cal/cm^2
0.07	0.24×10^{-2}	0.18×10^{-2}	0.21×10^{-2}	0.12×10^{-2}	0.09×10^{-2}	0.13×10^{-2}
0.12	0.47	0.38	0.43	0.37	0.28	0.32
0.15	0.62	0.54	0.60	0.50	0.42	0.43
0.19	0.86	0.75	0.81	0.66	0.60	0.58
0.25	1.19	1.05	1.13	0.96	0.84	0.79
0.35	1.65	1.52	1.58	1.35	1.22	1.14
0.54	2.28	2.18	2.18	1.95	1.68	1.71
0.82	2.76	2.65	2.56	2.35	2.01	2.15
1.36	3.05	3.04	2.84	2.45	2.29	2.45
2.18	3.14	3.09	2.89	2.49	2.31	2.55
4.08	3.21	3.19	2.91	2.25	2.40	2.57
6.00	3.20	3.17	2.83	2.53	2.41	2.57

TABLE A.9 ILLUMINATION VERSUS TIME, SHOT BOLTZMANN TRAILER

Time	Illumination
0.03	10.1×10^3
0.065	36.5
0.090	42.2
0.1 *	42.5 †
0.117	41.9
0.130	40.8
0.143	39.7
0.163	36.8
0.182	33.9
0.200	31.8
0.285	24.5
0.338	23.1
0.43	18.4
0.52	7.9
0.65	4.0
0.78	4.3
1.04	1.8
1.30	1.1
1.70	0.4
2.08	—
3.00	—

* Second maximum.
† Estimated.

TABLE A.10 ILLUMINATION VERSUS TIME, SHOT WILSON TRAILER

Time	Illumination
0.01	4.9×10^3
0.04	16.4
0.05	38.7
0.06	65.8
0.07	119.7
0.10	119.7
0.11	116.4
0.12	78.7
0.15	66.7
0.16	36.4
Recorder jammed for approximately 1.84 sec	
2.0	18.0
2.10	18.0
2.20	22.0
2.30	13.3
2.40	17.8
2.60	9
2.70	31

TABLE A.11 ILLUMINATION VERSUS TIME, SHOT PRISCILLA TRAILER

Time	Illumination
0.046	3.2×10^3
0.092	40.8
0.128	73.9
0.165	90.5
0.183	92.4
0.19 *	96.0 †
0.201	95.0
0.229	91.0
0.256	83.4
0.293	70.1
0.329	55.4
0.403	35.7
0.476	27.4
0.604	19.1
0.732	12.7
0.915	7.6
1.098	5.7
1.464	1.9

* Second maximum.

† Estimated.

TABLE A.12 ILLUMINATION VERSUS TIME, SHOT HOOD C-47 STATION

Time	Illumination
0.065	3.5×10^3
0.130	33.1
0.182	54.6
0.234	62.1
0.260	63.0
0.286	62.0
0.325	56.6
0.364	48.4
0.416	35.6
0.468	26.5
0.572	14.0
0.676	14.6
0.858	10.4
1.04	7.8
1.30	5.1
1.56	3.4
2.08	1.8
2.60	1.3
3.12	0.9
4.16	0.8
5.98	0.5
7.80	0.3

TABLE A.13 ILLUMINATION VERSUS TIME, SHOT DIABLO TRAILER

Time	Illumination
0.034	8.0×10^3
0.068	10.6
0.095	11.3
0.122	11.9
0.136	11.9
0.150	11.4
0.170	12.7
0.190	13.2
0.218	12.3
0.245	11.7
0.299	9.9
0.354	8.1
0.449	5.2
0.544	3.3
0.680	1.7
0.816	1.2
1.036	0.4
1.088	0.6
1.36	0.1